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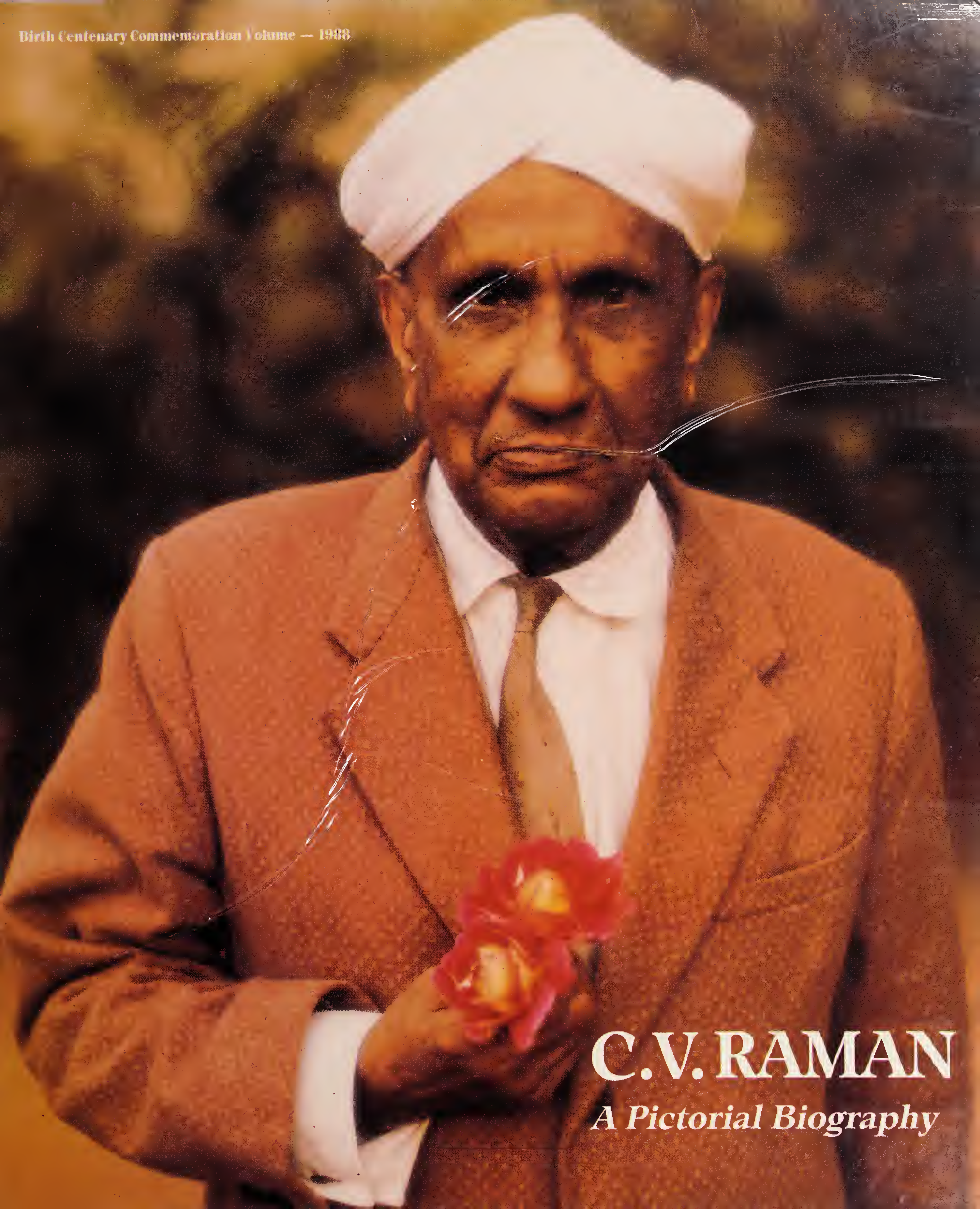

C.V. RAMAN

A Pictorial Biography

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Chandrasekhara Venkata Raman
1888 – 1970

The last photograph

COMPILED BY S RAMASESHAN AND C RAMACHANDRA RAO

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A Pictorial Biography

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Telephones: 342546, 342310 Telex: 0845 2178 ACAD IN

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PREFACE

This is both a preface and an acknowledgement. The origin of the pictures reproduced in this volume goes back to the golden jubilee of the Raman Effect in 1978 which was celebrated by an International Conference on Raman Spectroscopy in Bangalore. For that occasion, it was suggested that I should put together an exhibition of pictures related to Raman's history. I wrote to a large number of people, many of whom to my great satisfaction responded by sending me numerous photographs. Most of these were only snapshots but they covered the period and incidents which one desired to portray in the exhibition. Mr C Rajagopal, one of our best-known photographers, and his team at the National Aeronautical Laboratory, with the enthusiastic support of its Director, Dr SR Valluri, proceeded to copy and enlarge these pictures. Thanks to the help of Prof. G Srinivasan of the Raman Research Institute, these pictures were mounted to create an exhibition that was a major attraction during the conference and was much appreciated by the visiting delegates.

When the Raman Centenary Symposium was being planned it was suggested that a volume could be produced containing these pictures which would serve both as a permanent record and also be available to a larger group. But inexplicably, the negatives and the original photographs were "discovered" to have been lost, and the only way was to rephotograph the pictures that had been produced for the 1978 exhibition. This was undertaken by Mr C Ramachandra Rao the Staff Photographer of the Raman Research Institute, who managed to do a remarkable job as witness the pictures reproduced in this volume. Also included are some pictures in colour taken by him of some of the gems, minerals, shells, birds, butterflies and other colourful manifestations of Nature from the Raman collection.

What is unfortunate, however, is that all of the information regarding the original donors was lost. I am in the embarrassing position of not being able to acknowledge by name all those who were originally responsible for providing the material reproduced here. In fact this collection is the source from which material has been provided for any number of publications, books, films, videos, etc., relating to Raman and produced in recent years. May I record my heartfelt thanks to those now anonymous donors.

Finally, I would like to thank Mr MS Chintamani of the Eastern Press who was largely responsible for persuading me that a book such as this would be most appropriate to produce on the occasion of the Raman Centenary. Also, we owe to his personal interest, ability and care, the fine quality of this production.

It is said, and with reason, that one picture is worth a thousand words, and it is hoped that the pictures reproduced here will speak that eloquently. Even so I have been persuaded that it would add to the value of this volume if some written accounts were included at the beginning and the end to provide information relevant to Raman's history. The four articles in the beginning (all written versions of talks I gave) deal more with his life, career and style than with his science. At the end are reproduced the prefaces to the six volumes of Raman's collected scientific papers that were put together and published also in connection with the centenary. In these may be found an attempt to indicate in brief the range and content of the prodigious contributions of the remarkable scientist that was Raman. Pictures cannot convey this aspect of the man. And these prefaces are included only to whet the appetite for the repast that awaits any reader of his original works.

S Ramaseshan

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RAMAN

HIS LIFE AND HIS WORK

C.V.RAMAN*

I deem it a great honour to have been invited to deliver the first Raman Memorial Lecture. It was suggested that I should talk about C.V. Raman as it would be an appropriate subject this year, the 50th anniversary of the discovery of the Raman effect.

According to the modern view of science, nature can only be described. It cannot be explained. Like many extraordinary natural phenomena, Raman can only be described; he defies explanation.

This talk is not going to be a sociological or psychological study of Raman. I was his student and I knew him well for more than 25 years. For this very reason, mine is likely to be a prejudiced view.

Venkata Raman was born on the 7th November 1888 in the small village of Thiruvanaikkaval near Thiruchirapalli (in Tamil Nadu). His mother was Parvathi Ammal. His father R Chandrasekhara Iyer was a teacher in a local school. They had eight children, five sons and three daughters. Apparently, Chandrasekhara Iyer did not believe in family planning. Even if he did, and had stuck to the statutory limit, Raman would still have made it — as he was the second child, but the present speaker would not have been here to tell this story.

When Raman was three, his father accepted the post of lecturer in mathematics and physics in Mrs A V N College, Vishakapatnam (in Andhra Pradesh). It is interesting that in spite of the small salary (Rs.85/– p.m.) and a large family to support, Chandrasekhara Iyer had a good collection of books on physics, mathematics and philosophy written by the masters. He is also said to have played the violin exceedingly well.

Raman matriculated at 11, passed his F.A. (now–a–days called PUC or Intermediate) at 13, won a scholarship and joined the Presidency College, Madras. He passed his B.A. at 15 in the first class winning gold medals in English and physics. He passed the M.A. examination at 18 in

* The first C.V. Raman Memorial Lecture delivered at the Indian Institute of Science on 3 March 1978.

Chandrasekhara Iyer and Family. Raman *extreme left*

Some students of Presidency College. Raman *standing right*

Lokasundari, Mrs CS Ayyar, Mrs KV Iyer

January 1907. There is a photograph of him taken when he was in the Presidency College; a thin unimpressive boy with a *dhoti* draped in the South Indian (cylindrical) style, a cap and no chappals on his feet. There is a story that one of the professors at the college could not believe that this inconspicuous little lad was a student of the Presidency College. He asked Raman whether he had come there by mistake and caused general laughter in class. Very soon his professors found him so remarkably intelligent that they exempted him from attending all the science classes as they felt he had nothing to learn from them. (What understanding professors they were in those days!)

Some of the certificates that his teachers gave Raman are interesting: "The best student I have had in thirty years", "An unusual appreciation of English literature", "A facility in idiomatic expression", "Possessing great alertness of mind and a strong intellectual grasp", "A young man of independence and strength of character", etc.

At the age of 16 while measuring the angle of a prism using a college spectrometer—as thousands of us have done—Raman observed some diffraction bands. He investigated these and they formed the subject of his first publication in *The Philosophical Magazine* (*London*) in 1906. This was followed by a note in the same journal on a new experimental method of measuring surface tension.

These papers were communicated by the author himself and contain no acknowledgement of help received from anyone. It is also important to note that the Presidency College was at that time a teaching institution with no tradition whatsoever of research.

When he passed his B.A. examination his teachers suggested that he should go to England for further studies. But the Civil Surgeon of Madras ruled it out by disqualifying him medically saying that the rigours of the English climate would kill him. Raman is known to have said later "I shall ever be grateful to this man". In 1906 after his M.A. his teachers advised him to appear for the competitive examination which chose civil servants for the Finance Department. He passed the examination topping the list again.

Against all conventions of the time he arranged his own marriage with Lokasundari, who was then 13 years old. The story has it that on the first occasion he saw her, she was playing on the veena the Thyagaraja keertana "Rama ni samanam evaro". We shall never know whether it was by intent or by accident. Anyway, she insists that she still does not know if Raman married her for the extra allowance of Rs.150/– which the Finance Department gave to its married officers!

In 1907 the young couple went to Calcutta. He joined the Finance Department as Assistant Accountant-General. He was then $18^1/_2$ years old.

They rented a house in Scots Lane, off Bowbazaar Street. Within 6 or 7 days of his reaching Calcutta, while on his way to work by tram, he saw a sign which read "Indian Association for the Cultivation of Science." The address was 210, Bowbazaar Street. On his way back he knocked on the door, it was opened, we are told, by one Ashutosh Dey who was to be Raman's assistant for 25 years, the faithful Ashu Babu. Raman saw a dusty lecture hall and a large laboratory with a lot of even dustier equipment, mostly of the demonstration type.

Ashu Babu took Raman to Amrita Lal Sircar, the Secretary of the Association, who promptly handed over the keys of the Association to Raman when he heard of his plans to use it for research.

The Association had been established in 1876 by Amrita Lal's uncle, Mahendra Lal Sircar, a man of vision, who wanted to have an institution which was a combination of the Royal Institution of London and the British Association. It started off well. At every annual meeting Mahendra Lal advocated the importance of the cultivation of science by original research. There were many popular and scientific lectures in the early days but no research of any type. Subsequently, the institution had decayed, and in 1902 a despondent Mahendra Lal had declared, "I do not know how to account for the apathy of our people towards the cultivation of science". A few weeks before his death, he

stated "Younger men must come and step into my place and make this into a great institution".

At this time Raman had just passed his B.A. examination. In three years he was to discover the Association and turn 210, Bowbazaar Street into one of the important centres of original research in the world.

Young Lokasundari tells us of the routine — 5.30 a.m. Raman goes to the Association. Returns at 9.45 a.m., bathes, gulps his food in haste, leaves for his office, invariably by taxi so that he may not be late. At 5 p.m. Raman goes directly to the Association on his way back from work. Home at 9.30 or 10 p.m. Sundays, whole day at the Association. Truly, not an exciting life for a young bride.

She tells delightful stories of those days. There was one, of her going to the beautiful church at the end of Scots Lane when exploring the neighbourhood—but the brahmin cook (they had one, remember the Rs.150/– married allowance) left because he did not want to have any truck with people who went to church!

There is an interruption to Raman's work at the Association but not to his scientific activity. He is transferred to Rangoon (1909) and Nagpur (1910). At both places he converts his home into a laboratory and continues his work. He is back in Calcutta in 1911.

He and Ashu Babu are the only workers at the Association. Even so publications pour out. He starts the Bulletin of the Indian Association wherein he published massive monographs. In 1917 the Bulletin becomes the *Proceedings* and much later the *Indian Journal of Physics*.

What are the problems he tackles? It is remarkable that every one of them is connected with his direct experience thus arousing his curiosity. He has heard his father play the violin. He has worked with the sonometer and done Melde's experiment in college. So follow his papers on the bowed string, the struck string, the maintenance of vibrations, resonance, aerial waves generated by impact, the sounds of splashes, the singing flames, music from heated metals and many others.

Ashu Babu is his only collaborator and his name appears as a joint author in many papers. Raman is proud that there is a paper in which A. Dey is the sole author; published in the *Proceedings of the Royal Society* by his Ashu Babu who has never entered the portals of a university!

He investigates whether his feeling that the veena produces the most exquisite musical sound is due to sentiment or has a sound physical basis. The bridge of the veena is so cunningly constructed that the Helmholtz law, that the position at which the string is plucked cannot be a node, is violated. Thus this instrument produces innumerable harmonics making its sound closest in harmonic content to the human voice.

He knows that the normal stretched circular membrane as found in the western drum is "unmusical and just a noise producer". His sharp ear detects musical overtones in the sound of the mridangam and the tabla. He discovers that the heterogeneous loading of their membranes can produce harmonics — so that in the hands of the masters, the Indian drum is similar to a stringed instrument.

He publishes a beautiful paper on the acoustical knowledge of the ancient Hindus, for the Asutosh Mookerjee commemoration volume. He has become a world authority on sound and musical instruments.

A little earlier, Sir Asutosh Mookerjee, the Vice–Chancellor of the Calcutta University, offers him the Palit Chair of Physics. Raman decides to accept the offer for a salary less than what he is getting.

It is of some interest to know whether at this time he was successful as a Finance Officer. Apparently he was, for he has been congratulated many times by his "superiors" for his outstanding work. They are reluctant to let him go. The Member (Finance) of the Viceroy's Council writes: "We find Venkataraman is most useful in the Finance Department being, in fact, one of our best men".

Raman's decision produces consternation in the establishment. There may soon be Indianisation, they tell him. As one of the best officers, he may even end up as Member (Finance) in the Viceroy's Council — who knows? But Raman's mind is made up.

There is a problem, however, because one of the requirements for appointment to the Palit Chair is to have been trained abroad. Raman refuses to go to England to be "trained". The impasse is broken by Sir Asutosh changing the provisions of the endowment. What an administrator!

In 1919, Amrita Lal Sircar died and Raman became the Honorary Secretary of the Association having thus two laboratories to work in. He takes research students for the first time.

Science College, Calcutta

Under pressure from Sir Asutosh he goes to Europe in 1921, as a delegate to the Universities' Congress held that year in Oxford. During this brief visit he meets the famous scientists of England, J.J. Thomson, Rutherford, Bragg (Senior) and others.

Raman tells a story later how moved he was when Rutherford recognised him sitting in a back bench at a lecture and asked him to come and sit next to him.

Like any good tourist he takes in the sights of London and visits St. Paul's Cathedral. He marvels at its whispering gallery, does a few experiments, and publishes two papers — one in *Nature* and the other in the *Proceedings of the Royal Society*.

It was on this voyage that Raman came face to face with the grandeur of the Mediterranean sea, its beauty, its moods and in particular its blueness. The more he saw of it, the more did his wonder grow.

Lord Rayleigh, who had explained the blue of the sky as due to scattering by the molecules in the atmosphere, dismissed the blue of the sea with the statement "The much admired dark blue of the deep sea .... is simply, the blue of the sky seen by reflection". Raman demolished this idea by an extremely simple experiment during the return voyage. He quenched the reflection of the sky in the sea by observing it at the Brewsterian angle through a polarising nicol prism. Even with the sky reflection so extinguished, he saw the surface of the sea glowing with a vivid blue which appeared to emerge from inside the water indicating that the blueness of the sea was due to scattering by the water.

What a sight he must have been on the ship — this turbanned brown Indian, with his nicol prisms and cardboard tubes, running from side to side of the ship, collecting sea water in bottles from the depths of the oceans. All this while others were busy playing shuttlecock and battledores — the real mad scientist of fiction.

Even on board the ship he felt that the Einstein-Smoluchowski concept of thermodynamic fluctuation — which was developed to explain special optical phenomena near the critical point — could be extended to explain molecular diffraction in liquids. On his return to India he started three most fruitful lines of investigation:

1. The scattering of light by liquids.
2. The scattering of X–rays by liquids.
3. The viscosity of liquids.

Many here may not know that the earliest work on the scattering of X–rays by liquids was done in India. Raman and his group developed an effective theory and confirmed the shapes of many molecules and deduced the nature of their aggregation in the liquid state. Raman once said wistfully "We were so preoccupied with light scattering that we did not apply the idea of Fourier transforms to X–ray scattering in liquids although we were so close to it". This was done later by Zernicke and Prins in 1927 — the famous Raman-Ramanathan paper was in 1923.

In 1923 he advanced a theory of viscosity which was quite a success. It was used by Staudinger, the famous polymer chemist, to explain the viscosity of polymers.

Within a few weeks of his return from England he (and Seshagiri Rao) had measured the intensity of the molecular scattering of light from water. They established that the Einstein-Smoluchowski concept of thermodynamic fluctuations could be extended to explain molecular scattering almost quantitatively. As a result many of his students were put to studying molecular scattering in liquids and vapours.

It was in 1922 that he wrote and published his monograph "The molecular diffraction of light". In it he raised such questions as to what would happen in a black body enclosure if the exchange of energy took place by molecular scattering. He considered in detail how energy could be transferred between the quantum of light and the molecule. He seems to have been convinced that the quantum nature of light should reveal itself in molecular scattering. We note that all this was a year before the discovery of the Compton effect.

In April 1923 KR Ramanathan, the oldest and among the most distinguished of Raman's students, at Raman's suggestion, made a serious study of the scattering of light in water. Sunlight was focussed on the liquid and the scattered light was seen as a track in the transverse direction. A system of complementary filters was devised, each filter completely cutting off the light transmitted by the other. When the incident light was passed through one, and the scattered light viewed through the other, no track should have been visible, if there had been no change of colour in the process. But the track could be observed. This was attributed to a "weak fluorescence" due to impurities which were believed to be present. This "weak fluorescence" was not completely depolarised (as true fluorescence should have been) and the amount of depolarisation changed with wavelength.

Ramanathan wrote much later: "Raman was not satisfied with the explanation that it was due to fluorescence. He felt that it was characteristic of the substance and wondered whether it might not be akin to the Compton effect in X–ray scattering" (where a change in wavelength of X–rays scattered by atoms had just been discovered that year). Even after repeated slow distillation of the liquids in vacuum the "weak fluorescence" persisted undiminished. The same effect was also observed later in many organic liquids, by KS Krishnan, another of Raman's distinguished students who had just joined him.

In winter of 1927 Raman went on a vacation (or perhaps a lecture tour) to Waltair. The Compton effect was on his mind. He had calculated that the true Compton scattering could not be observed at optical wavelengths. He considered the interaction of X–rays with the electrons of the atom — and using the concept of fluctuations, which was so successful in explaining the molecular scattering, he derived the relationship now famous as the Compton-Raman formula. The derivation was completely classical wherein Raman showed that the coherent scattering (corresponding to Thomson scattering in X–rays and to Rayleigh scattering in light) is proportional to the square of the number of electrons in the atom whereas the incoherent scattering (Compton scattering) is proportional to the number of electrons.

In January 1928 Venkateswaran who was on the task of purifying many liquids made the remarkable observation that in pure glycerine the scattered light was greenish in colour instead of the usual blue, and the radiation was strongly polarised.

In the last week of January, Raman apparently decided to settle the issue. He asked KS Krishnan who had been doing excellent theoretical work on mechanical, electrical and magnetic birefringence to take up experimental work again and to follow up Venkateswaran's observations. Raman persuaded Krishnan that it was not healthy for a scientific man to get out of touch with actual

experimentation for any length of time (Krishnan's last experimental work was done 18 to 20 months before).

Krishnan set up the experiment for the study of the scattering of light in organic liquids and vapours — but this time he used larger lenses (7 inches diameter) so the intensity of the track was very much greater. On the 7th February he noticed that all his liquids exhibited the famous "weak fluorescence" observed by Ramanathan and further that the polarisation of the "fluorescent" light was greater the smaller the anisotropy of the molecule.

Professor Raman (according to Krishnan) personally verified that all the liquids exhibited this phenomenon. He records that Raman rushed to his house quite excited to tell him that he was certain that their observations in the morning were related to the Kramers-Heisenberg process they were looking for all these years. On the 16th February they sent a note to *Nature* repeating the arguments used in Raman's classical derivation of the Compton effect and suggesting that "the modified radiation could arise from the fluctuations of the molecules from the normal state".

While the analogy with the X–ray case had been made much closer, it was apparent that the phenomenon was not fully understood and the observations continued, Raman making most of them himself.

On the evening of the 27th, Raman decided to view the "fluorescent track" through a direct vision spectroscope, but by the time Ashu Babu set it up, the sun had set. Next morning the first observation was made of what is now known as the Raman effect. The spectroscope showed that the track contained not only the incident colour but at least another separated by a dark space.

Ashu Babu helped to set up a mercury arc, a light source known for its sharp monochromatic lines. Using a filter in the incident light which cuts off all the visible light longer than the indigo 4358 A.U. line the direct vision spectroscope showed not one but two sharp lines in the blue-green region.

The announcement of the discovery was made to the Associated Press the following day, the 29th of February 1928.

When a photograph was taken of the spectrum using a Hilger Baby quartz spectrograph, the shift in frequency of the new line from the incident one was identified with the change in the energy of the vibrational state of the molecule. Further, modified lines were observed having frequencies both lower and higher than that of the incident light indicating that the incident photon could gain or lose energy when scattered by the molecules.

Story goes that the note to *Nature* sent by Raman announcing the discovery on March 8th was rejected by a referee but published anyway by the editor.

The following is an extract of the cable to *Nature* from Prof. RW Wood, the distinguished optical physicist of Johns Hopkins University, U.S.A:

> Prof. Raman's brilliant and surprising discovery; I have verified his discovery in every particular. Raman's discovery thus makes it possible to investigate remote infrared regions hitherto little explored.
>
> It appears to me that this very beautiful discovery which resulted from Raman's long and patient study of the phenomenon of light scattering is one of the most convincing proofs of the quantum theory of light.

Before long many laboratories around the world took up the study of the Raman effect in simple molecules. But in Raman's laboratory the accent was on the study of more fundamental problems connected with the physics of the liquid and solid state using the Raman effect as a tool.

Raman was awarded the Nobel Prize for his work "on the diffusion of light and for the discovery of the effect named after him". His Nobel lecture is a masterpiece of composition relating the exciting story of the persistent efforts from 1921 to 1930 giving a detailed account of the contribution made by each of his collaborators.

There are two stories that are indicative of the character of this incredible man and his supreme self-confidence. Raman was elected a Fellow of the Royal Society in 1924. At the meeting to felicitate him, he is known to have said — while he appreciated the honour done to him he did not consider it the ultimate and that he would get the Nobel Prize for India within 5 years!

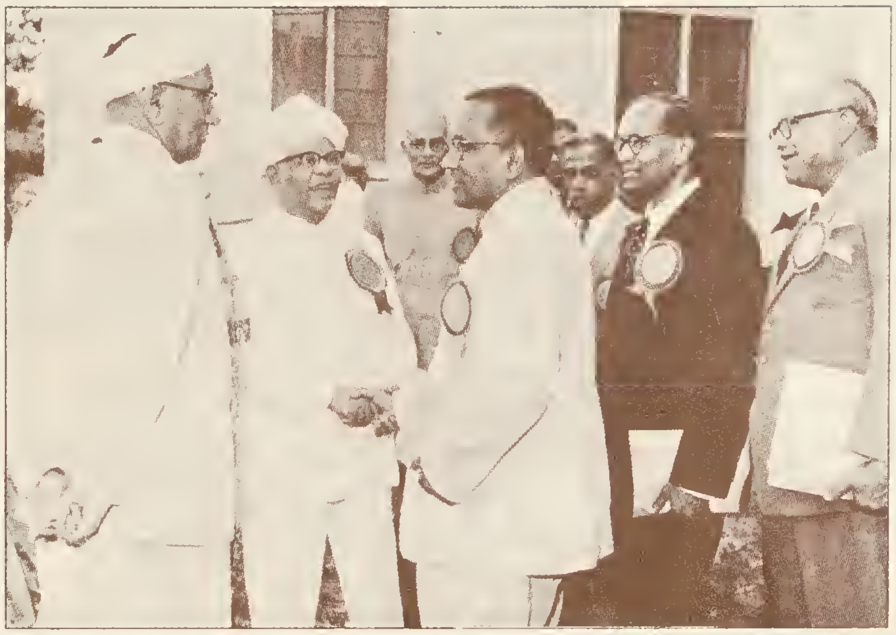
Nobel Prizes are announced in the second or third week of November. The meetings of the Nobel Committee are held in the highest secrecy and the awards are announced in November about a month before the prize giving ceremony in mid-December. It would have been surprising enough that Raman could leave by steam ship after receiving the news by telegram to reach Stockholm

in time for the ceremony. It is now a historical fact however that Raman had booked two tickets for himself and his wife in July that year to enable them to reach Stockholm in early December!

In 1933 Raman was offered the Directorship of this Institute (Indian Institute of Science) which as you all know was started by that visionary JN Tata whose memory is also being honoured today. Raman was at first in two minds about taking it up, but later decided to accept the offer. Before leaving Calcutta he made sure that his brilliant pupil KS Krishnan was appointed the Mahendra Lal Sircar Professor at the Indian Association. Regarding Raman's move to Bangalore, Fermor (the Director-General of the Geological Survey), the President of the Science Congress that year, said "At present Calcutta may be regarded as the centre of scientific research in India. But with the transference to Bangalore of one of the leading investigators, Calcutta will have to guard her laurels".

This was the year many famous scientists were fleeing Germany to escape from the tyranny of Hitler. No sooner had he come to Bangalore Raman made attempts to get some of them to India. He succeeded in appointing Max Born to an extraordinary Chair of Physics which he created at the Institute. There is a letter from Schrödinger, the originator of wave mechanics, saying that Raman's offer had arrived a bit too late as he had just accepted an offer from Dublin — regretting that he could not settle in the land of the Upanishads! Ewald, Peierls, Kuhn and many others were also in Raman's list. Years later I once asked him about his attempts to bring these scientists to India. He replied that he had always been against young Indians going abroad to be initiated in scientific research because it would have been done in an environment so completely different from what exists in India. This type of training could have made them useless in our country. If great minds like Born and Schrödinger who were seeking a country to adopt had been provided with a home here, a real scientific movement could perhaps have been started in the country. Unfortunately Raman was prevented from succeeding in this attempt.

In inviting these scientists, he had characteristically not taken permission of the management of the Institute. For this and other such reasons he was forced to resign from the Directorship of the Institute but he managed to retain his Professorship. I am not familiar with the complete story of this "demotion" but I certainly plan to look into the history of this incident. The formal charges were, in any case, definitely flimsy. While Raman could



Academy meeting at Annamalainagar

admittedly be difficult, one wonders whether it was not just due to the "scientific politics" of that time.

"What is highest is Envy's mark" said Ovid.

In 1934 Raman started the Indian Academy of Sciences and the best young scientists from all over India were elected as Fellows. They began publishing in its journals. It is remarkable that for twenty years right up to 1954 the Proceedings of the Indian Academy was considered among the top journals of the world in physics and chemistry. The annual meetings of the Academy, which Raman used to call his travelling circus, were held in university towns. The most distinguished scientists of the country were always there discoursing and lecturing. But Raman was always the star performer.

I particularly remember the meeting of 1941 in Nagpur where I was a student of the B.Sc.(Hons.) class. KR Ramanathan was there, and so was Bhabha. I even remember young Vikram Sarabhai, and there were a host of others. It was a coterie of scientists talking only science. It was so exciting for me and all the young people from the university. Raman, as always, gave the presidential address, and ended the three-day session with a popular lecture. He always drew very large audiences, and this time there were more than 5000 to listen to him. Every man and woman, every boy and girl went back dazed, feeling they had discovered the beauty and the simplicity of science.

During my career I have heard many, many scientists talk and lecture. But Raman in his heyday was perhaps the best. This opinion, I know, is shared by many of my

generation. What was it that made his lectures so gripping? It was not just his mannerisms or his humour — he made his audiences roar with laughter. To him, giving a lecture was clearing up things in his own mind. He talked of only those things about which he felt intensely, of those things which he understood or wanted to understand. He saw things in their simplest and most basic elements. He made the audience feel that they could have seen it all by themselves (which of course they had not).

He was perhaps the greatest salesman science has ever had in this country. How many gifted young men of the last generation took to science because of having listened to him once!

A word about him and his students. He usually selected very talented young men (and on a few occasions women) to work with him. So powerful was his influence that his students rose to heights which they themselves could not have imagined possible. He was like a conductor who extracted the best music from his orchestra. It was not uncommon that some students who had done extremely well when they were with him, once deprived of his influence were never heard of again!

He used his personal prestige and that of the Indian Academy to encourage scientific talent, wherever it was found and in whatever field it showed itself. From 1924 till about 1954 (when "big science" was established in India) he was one of the main sources of encouragement for scientific talent in the country. In this respect his service to the nation was unique.

As with the Indian Association he made the Physics Department of this Institute a centre of world renown. He worked on such delectable things as the plumage of birds, the colours of shells, the hues of old iridescent glass, and soap bubbles. Along with Nagendra Nath, he propounded the now famous Raman-Nath theory of the diffraction of light by ultrasonic waves based on a concept so simple and so elegant. A plane wave of light when it passes through an ultrasonic wave field is speeded up in regions of rarefaction and slowed down in the regions of compression to emerge as a corrugated wave-front. This idea cleared the air of many of the theories that were extant and was hailed all over the world. The year after the Raman-Nath papers appeared in the Proceedings, the circulation shot up noticeably.

His school again had a renewed look at the scattering of light by liquids. According to Brillouin, thermodynamic fluctuations in the liquid can be broken up into waves (the Fourier components) which would scatter light with an associated Doppler shift from which the velocity of these waves could be measured. Such measurements were made by Raman's group. But what was more exciting was the discovery that viscous liquids almost behaved like solids at these high frequencies sustaining not only longitudinal but also shear waves. They were able to get the rigidity modulus for these liquids at these high frequencies!

Raman's interest in diamonds is well known. As a direct result of this, his school carried out pioneering studies of the thermo-optic behaviour of solids, their photo-elastic, magneto-optic properties, fluorescence, and second order Raman effect, infrared spectroscopy, etc. It is perhaps not well known that X–ray topography was discovered in this laboratory while studying the imperfections in diamond.

In 1948 he retired from the Indian Institute of Science and was made a National Professor. He had hoped to start a small institute for himself with his life's savings, where he could retire and enjoy science. But it so happened that he lost most of his savings in a "south sea bubble" investment. He was sixty then and to anyone else it would have been an impossible situation. But Raman was undeterred. He went round the country and collected money.

"Our greatest men were beggars" he said, "the Buddha, Shankara or even Gandhi". He succeeded in collecting enough to start the Institute but not to sustain it.

He then launched courageously on a new project. Advised and aided by an old student, he used what remained of his savings to start a couple of chemical factories, the dividends from which were sufficient to support his Institute and to keep it independent of government grants. Raman was never a member of too many committees, but on his retirement he resigned from every one of them. There is a story concerning his reactions when a feeler was sent out to see whether he would like the Vice-Presidentship of India. He is reported to have had a hearty laugh and asked "What shall I do with it?"

For some years there was no equipment or even electrical power in his Institute. He arranged his famous mineral and crystal collection and commenced his researches on the colour and iridescence of minerals and gems. It is remarkable how much information he could extract by just sending a beam of light into a gem and observing the scattering. This led him on to his classical papers on the optics of heterogeneous media.

He took students but this time with greater discrimination, and once more he made his laboratory into a great centre of research. There were many outstanding research publications from the Institute on the generalised theory of interference, the theory of optical activity in crystals and a variety of other subjects.

It was during this period that he launched upon his researches on the physiology of vision and on floral colours. He was happy surrounded by his exquisite roses, the jacarandas and the bougainvillaeas, the hibiscus and the morning glories, and enjoyed studying them.

Perhaps the least understood and the most criticised phase of Raman's life was when he suddenly chose to make himself a recluse. He refused to accept even the marginal support he was getting from the Government. Two ministers who visited him once to offer support were told "Why do you want to despoil the only oasis of freedom in the country". He built high walls around the Institute and put up a prominent sign stating that visitors were not welcome. His attitude, particularly towards the Government, became one of utmost cynicism.

To those who knew him, he was a soul in agony. He was veritably like Timon of Athens — bitter and cynical.

To Raman, scientific activity was the fulfilment of an inner need. His approach to science was one of passion, curiosity and simplicity. It was an attempt to understand. To him science was based on independent thought, combined with hard work. Science was a personal endeavour, an aesthetic pursuit and above all a joyous experience.

The Indian scientific scene of that time presented to him a very strange picture. The establishment seemed to believe that scientists cannot be grown in the country as they sent all their bright young students abroad for 'training'. He saw the expenditure of large sums of money — in the belief that science, and therefore technology, will automatically be created. He saw the replacement of quality by quantity. He saw the choice of research topics — dictated mostly by foreign fashions and this hurt him most.

I shall make no value judgement here, but we can imagine what he would have felt. A total negation, in the name of science, of all the values he had lived by. He must have felt that his example had been totally in vain and he blamed the establishment for it.

"My life" he once cried, "has been an utter failure". "I thought I would try to build true science in this country. But all we have is a legion of camp followers of the West".

To my mind the agony of Raman can only be compared to that of Gandhi in Noakhali when he too found that all his life's work was at nought, the apostle of non-violence witnessing his countrymen beating each other to death.

It was in this phase that Raman resigned from the Royal Society of London.

Raman did come out of the slough of despond finally. Almost every day he was seen taking school children and college students round his Institute regaling them with stories and showing them experiments. He began accepting lecture engagements. His charisma was still potent with the younger generation. He attracted enormous audiences, and university halls began overflowing again. He made fervent pleas to the Government to improve schools and university education and university research.

He said "When we want to achieve — whether it be in science or in anything else we must first learn to use the resourccs we have in plenty. As a nation what are the resources we have in plenty — human beings, of whom at least a third are young. This is our real strength. If they are enthused and if they are instilled with a spirit of adventure, the sleeping giant will wake up and we can conquer the world".

Raman was, of course, the supreme egotist. But in private conversation he often showed such an unbelievable scientific humility as to make one wonder which was his true self. He always told people what he felt and in this process hurt many. He was a man of emotion and he could get violently angry. Some of us still remember how he wept like a child during one of the Academy lectures when pictures were shown of children of our land suffering from nutritional ailments. He had an incredible sense of humour and he could keep us roaring with laughter just describing what could have been commonplace incident.

He was a very simple man, quite childlike — sometimes even childish.

The science administrators of today would even think him naive. For example he believed that the only method of promoting science was by doing it, and to him the professional organisers of science were an abomination. "For such people" he said "the so-called organisation of science becomes more important than science itself or its values".

To him the simplest observations that he could make by just looking around him were worthy of the deepest scientific investigation. He demonstrated over and over again that a deeper understanding of these everyday phenomena paved the way for the discovery of fundamental laws. He relied greatly on intuition — in fact Max Born once said "Raman's quick mind leaps over mathematics".

Anyone who met him could not but be struck by his zest for life. Born refers to this in his letter to Lord Rutherford written in the later half of the thirties. Born says "There is no Indian physicist of the rank of Raman. No man can compare with him in regard to vigour or intensity. This European intensity which Raman exhibits to a marked degree would make any average Indian scientist suspicious of him".

His exuberance was infectious. Chatting with him for some time was like taking a tonic.

To those of us who knew him well, what struck us most was his intense love of and the preoccupation with nature — the colours of birds, the sheen of the beetles, the blue of the sky, the spectacular hues of the coronas and the glories that surround the Sun and the Moon, the extraordinary beauty of minerals, crystals and gems. These not only thrilled him but formed the subject matter of his scientific studies.

A few months before he died, I remember, while walking with him one evening amongst the eucalyptus groves that he loved, he stopped me in his characteristic manner and pointing towards the sky said: "Have you seen anything so beautiful?"

Above, one saw little wisps of multi-coloured clouds passing close to the Moon, which gleamed over the shimmering leaves of the trees — trees which appeared like nature's own cathedral.

"This is happiness" he said. "That we should be alive, and that we should be endowed by nature the faculty to perceive this fleeting vision of beauty — this is happiness indeed".

The banquet after the Nobel ceremony. Raman with turban *centre of extreme right row*

THE PORTRAIT OF A SCIENTIST – C.V.Raman*

1. Raman and Ramanujan

When one thinks of Indian science at its best, two names spring foremost to one's mind — the towering figures of Ramanujan and Raman, both of whom were born about a hundred years ago. And when they grew up, they did things that made the world sit up and take note. The first was one of the greatest mathematicians of the world, while the other was an experimental physicist *par excellence* who won for India the Nobel Prize. The mathematicians of the world desired to present Mrs Ramanujan with a bronze bust of Ramanujan. The U.S. mathematician Richard Askey persuaded the sculptor Paul Granlund to undertake the making of this bust. Prof. Chandrasekhar and his wife Lalitha graciously offered to present one of the copies to the Indian Academy of Sciences. At that time the Chicago Astrophysicist wrote:

> As a companion to the bust of Raman so that the bust of the greatest physicist of India could be along with that of the greatest mathematical genius of our times who happened to be an Indian.

Nothing is so tedious as a twice-told tale, says Shakespeare. The story of Raman and the Raman Effect has been told all over India many times during this centenary year of his birth. I shall therefore have to fall back on the ancient tradition in India that the oftener one hears of the tales of the achievements of our great ones and heroes, the more merit does the listener acquire!

2. Calcutta and the "Association"

I am honoured that I have been invited to speak at this Raman Centennial held at the Indian Association for the Cultivation of Science. Raman's first posting as Assistant Accountant-General (when he was just eighteen) was in Calcutta, then the capital of the Indian Dominion. Within a few days of his reaching Calcutta, on his way to work one morning he saw a sign, "Indian Association for the Cultivation of Science". It was then at 210 Bowbazar Street. That evening while going back from work he sauntered in to find out what it was. It was just being locked up by Ashutosh Dey, subsequently known to all as Ashu Babu, who was destined to spend twentyfive years as Raman's assistant and the gentle tyrant ruling over his laboratory with an iron hand. Raman was told that Mahendra Lal Sircar had established this Institution in 1876 but that it had not prospered. Just before his death Mahendra Lal had said, "Younger men must come and step into my place and make it into a great institution."

When Amrita Lal Sircar, the Secretary of the Association, met Raman, he knew that the young man his uncle had dreamt of had at last arrived. So he handed him the keys permitting him free use of the laboratory. Raman wasted no time in starting serious scientific research. He had a 10 to 5 job in the Finance Department and so work at the Association was always after "office" hours, even going late into the night. In one paper Raman thanks his assistants "for their working during hours when few institutions, if any, would even have remained open". He made the dying dream of Mahendra Lal Sircar a reality and the Association a great centre of research.

And on this occasion I also salute Calcutta, this much maligned but vibrant city, where things always seem to

* Invited lecture delivered at the celebrations of the Birth Centenary of C.V. Raman and the Diamond Jubilee of the Raman Effect held at the Indian Association for the Cultivation of Science, Calcutta.

happen, where there is ever an intellectual ferment. India has had three Nobel Prize winners – the philosopher-poet Rabindranath Tagore, the experimental physicist Chandrasekhara Venkata Raman, and the gentle practical saint Mother Teresa. Is it not remarkable that it was this incredible city which provided each one of them the background and support for their work? I am of course afraid of suggesting to this great city or to its fathers that they reduce its din, its dirt and its smells, lest in attempting to do this, Calcutta may also lose its glorious tradition of breeding Nobel Prize winners!

3. Early life

C.V. Raman was a phenomenon. He had the eye of an artist and the vision of a poet. He could laugh like a child and rage like one possessed. When his intuition was at its best few could match him. He was for ever in the centre of a storm which, often, was generated by himself. He had elements in him which could easily make him a mythical figure. But I shall try my best in this presentation to avoid doing this. For Raman was really a man of flesh and blood. I shall try to paint him (as Cromwell told his portrayer to do) "with pimples, warts and everything".

There is no denying that there was some magic about Raman. He finishes school at the age of eleven, by which time he has read the popular lectures of Tyndall, Faraday and von Helmholtz. He joins the Presidency College, Madras, at thirteen and is immediately spotted by his teachers, who exempt him from attending the usual lectures. He spends much of his time in the library consuming Lord Rayleigh's scientific papers, and bicycles twice a week to the Connemara Library, several miles away, to read the latest scientific journals. He learns from Helmholtz's *Sensations of Tone* what research really means, and ventures boldly into experimental research in a college laboratory which has had no previous tradition of research in physics. He works on acoustics and optics, and publishes original papers in *The Philosophical Magazine* and *Nature*. He corresponds with Lord Rayleigh who was then the President of the Royal Society. To earn a living when he finishes college he sits for the Financial Civil Service examination and tops the list. He arranges his own marriage with Lokasundari, who is thirteen and a half years old. He is appointed Assistant Accountant-General in 1907 and is posted to far-off Calcutta, Nagpur, and Rangoon in Burma, where he earns a name in the Finance Department as one of its finest officers. In fact he acquires a reputation that he may even become the first Indian Member for Finance in the Viceroy's Council. Sir CD Deshmukh, the first Governor of the Reserve Bank of India, said that its starting was based on a paper initiated by Raman in those early days. But all this was incidental to Raman.

4. His motivations

But during those ten years 1907 – 1917 — rain or shine, Nagpur or Rangoon — he did experimental research at home under the most adverse and trying conditions or at the Association when he was in Calcutta. Colonial India was noticed by the scientific world because of his activities. The Vice-Chancellor of Calcutta University Asutosh Mookerjee — the Tiger of Bengal — also noticed him and suggested he leave government service to join the University as a professor. To the horror of some and the amazement of all Raman accepts the professorship on a salary of about half of what he was getting.

What were the motivations of this strange man? He wrote a few years later:

> In my case strangely enough it was not the love of science, nor the love of Nature [both of which he had in abundance] — but an abstract idealisation, the belief in the value of the Human Spirit and the virtue of Human Endeavour and Achievement.

Raman visiting a laboratory

When I read Edwin Arnold's classic *The Light of Asia,* I was moved by the story of the Buddha's great renunciation, of his search for truth, and of his final enlightenment. It showed me that the capacity for renunciation in the pursuit of exalted aims is the very essence of human greatness.

5. Lokasundari Raman

But before I start seriously on Raman himself let me pay tribute to one without whom he might not have done half the remarkable things he did in science. I refer to his wife, the gracious Lokasundari Raman.

We were all, in a sense, not sorry that he died before her; for what would he have done without her? Her devotion to him was what we read of in our epics. But she was a tough character, yes she had to be tough to be his wife. She was never afraid of telling him when he was wrong and was ever advising him on what he should *not* do or have done. She had, by choice, married a hurricane and she did try to keep it under control for 63 years but never really managed. And when the hurricane died she was left all alone.

6. Some attitudes

Raman was typically Indian, he never gave up his old traditional hairdo. In public he always sported a turban. "How else" he quipped, "could Lord Rutherford have recognised me in that crowded Cavendish lecture hall?" Unlike most Indians, he was not at all superstitious and he despised rituals. On the night of his death, his wife asked him to take the name of God. He was dying but he said "I believe only in the Spirit of Man" and talked of the Mahatma, the Christ and the Buddha and then made a request, "Just a clean and simple cremation for me, no mumbo-jumbo please."

Raman in traditional Indian dress

7. The Raman Effect

The discovery of the Raman Effect is a saga of a single-minded man pursuing the holy grail with a stamina and persistence never before or since seen in this country. On his first voyage to Europe in 1921, the visual beauty of the Mediterranean bewitched him. Lord Rayleigh was of the view that this blue was due to the reflection of the sky in the water. Raman disproved it by a simple experiment he did on board the ship. He quenched the sky's reflection with a nicol prism at the Brewster angle and found that the blue colour "far from being impoverished by suppression of the sky reflection was wonderfully improved thereby". He showed thus that the blue is due to molecular scattering and established quantitatively that the Smoluchowski – Einstein fluctuations were its basic cause. He then wrote the celebrated monograph *The Molecular Diffraction of Light* in 1922.

From a thought experiment, imagining scattering to take place in a black-body enclosure, he obtained the result that Rayleigh scattering must be a discontinuous process caused by photon collisions. He argued how this can be reconciled with Maxwell's electromagnetic equations and ended by saying, "Rather the Maxwell's field equations must be altered to introduce the quantum of action" — a concise statement of the basic goal of quantum electrodynamics to be developed much later by Dirac, Heisenberg and Pauli. Max Born told Nagendra Nath later, "It was astounding to know that Raman realised as early as 1922 that the field equations themselves have to be quantized." No wonder Born stated, "Raman's mind leaps over mathematics."

Intuitively Raman concluded that the interaction of the photon with a molecule must reveal itself by a change in colour. Even the first experiment (with KR Ramanathan) in 1923, using sunlight filtered through a colour filter and observing the scattered light track with a complementary filter, revealed this change of colour. Ramanathan thought that this "weak fluorescence" was caused by impurities. Raman refused to accept this impurity hypothesis as the track exhibited polarisation. In 1925 the attempt to record the spectrum of this "weak fluorescence" track by S Venkateswaran failed.

A European scientist visiting the California Institute of Technology recalled that he met a scientist from India who imagined that he was going to discover a quantum effect in light scattering which would win for India the Nobel Prize*. "I thought that he was crazy. The incredible thing is that this man does make the discovery and does get the Nobel Prize six years later!"

In 1925 Raman writes to GD Birla, the industrialist and friend of Gandhi, that he needs money for an instrument called a spectrograph: "If I have it, I think I can get the Nobel Prize for India".

Raman gave a novel derivation for the Compton Effect formula. He concluded that there must be an optical analogue in which a quantum of radiation can be absorbed in part and scattered in part.

In December 1927 the so-called polarised "weak fluorescence" was observed again in pure glycerine with greater intensity. The observation was made by S Venkateswaran who now had a job in the Alipore Test House and so was only a part-time worker at the Association. Raman had picked up the scent again and wished to resume the chase. He now had a larger lens which would double the incident intensity and he wanted someone to use the winter sun of Calcutta (with its cloudless sky) all the time for the experiment. So he persuaded his best student KS Krishnan who had been doing only theory for the previous three years to come back to experiments. Krishnan starts to work on January 29th or 30th 1928, and, according to his diary, Raman and he work together continuously and detect the polarised "weak fluorescence" in *all* the liquids, gases and solids they examined. A later entry says: "Professor suddenly came to our house at 9 P.M. He came to tell me what we had observed must be the Kramers – Heisenberg Effect that we had been looking for all these years. We decided to call it 'modified scattering'."

On February 28th, Raman examined the scattered track with a direct vision spectroscope and found that the classical and modified scattering appear in the spectrum as separate regions with a distinct dark region between them, a clear demonstration of a change of wavelength in scattering.

Raman was in a state of euphoria — a man who had at last come to the end of the trail he had been following for seven years. Krishnan's diary says: "He ran about the place shouting all the time. He asked me to call everybody in the place to see the effect."

They then used the mercury vapour lamp and photographed the first ever Raman spectrum with a Hilger baby quartz spectrograph. Besides the incident radiation several other lines were present in the scattered spectrum. A lecture entitled "A new radiation" was given on March 16th 1928 in Bangalore and was printed in the *Indian Journal of Physics* on March 31st 1928. Three thousand reprints were posted the next day to all the leading laboratories of the world!

8. Sommerfeld's visit to India

Sommerfeld, the author of *Atombau und Spectralinien,* who shaped theoretical physics in Germany by the style of his lectures and his quality as a teacher, decided to visit the United States of America. Raman invited him to Calcutta. Sommerfeld decided to take the eastern route as he was "attracted to India by its fantastic religion and its remarkable philosophical systems."

Sommerfeld arrived in India, and promptly fell ill, as all westerners must! He came to Raman's laboratory on October 4th (1928) and Raman and Krishnan showed him the experimental verification of Sommerfeld's formula for the propagation of radio waves round the earth using a ball just 1 mm in diameter and light as the electromagnetic radiation. "Everything at the Institute very good" said Sommerfeld, and being an honest man, added, "but the bathrooms terrible". Sixty years have passed but we still uphold this tradition with bathrooms! On October 6th he says with great satisfaction: "Saw the Raman Effect visually; heard a wonderful lecture by Raman. Saw the Raman Effect in ice, also that we can see rotation of molecules as 'Modified Radiation'." So convinced was Sommerfeld of the reality of the Raman Effect that he arranged to propose Raman for the Nobel award. He stated when he left, "India has suddenly emerged in research as an equal partner with her European and American sisters."

Another incident! Immediately after the discovery Raman went out for a walk along the Hooghly with SN Bose — the inventor of Bose statistics — who was a member of Raman's Physics Department at the University. Satyen Bose told him: "Prof. Raman, you have made a great discovery. You will surely get the Nobel Prize for it."

* The reader will note from this and more to come that Raman had an obsession about the Nobel Prize. I used to think that this was because it was first instituted when he was at the impressionable age of thirteen and because so many of his heroes in science like Röntgen, Lorentz, Zeeman, Becquerel, Pierre and Marie Curie, his own Guru *in absentia* Rayleigh, Lenard, JJ Thomson and Michelson were its recipients during his college career. But it became clear to me later that this, as everybody knows, is a widespread malady amongst scientists.

9. The Nobel ceremony

In 1930 Raman was awarded the Nobel Prize. Amongst those who nominated him were Lord Rutherford, Niels Bohr, Louis de Broglie, Charles Fabry, Jean Perrin, Eugene Bloch, CTR Wilson and the Russian scientist Chowlson. There was one nomination for Raman and Heisenberg, two for Raman and RW Wood, and one for Raman, Landsberg and Mandelstam.

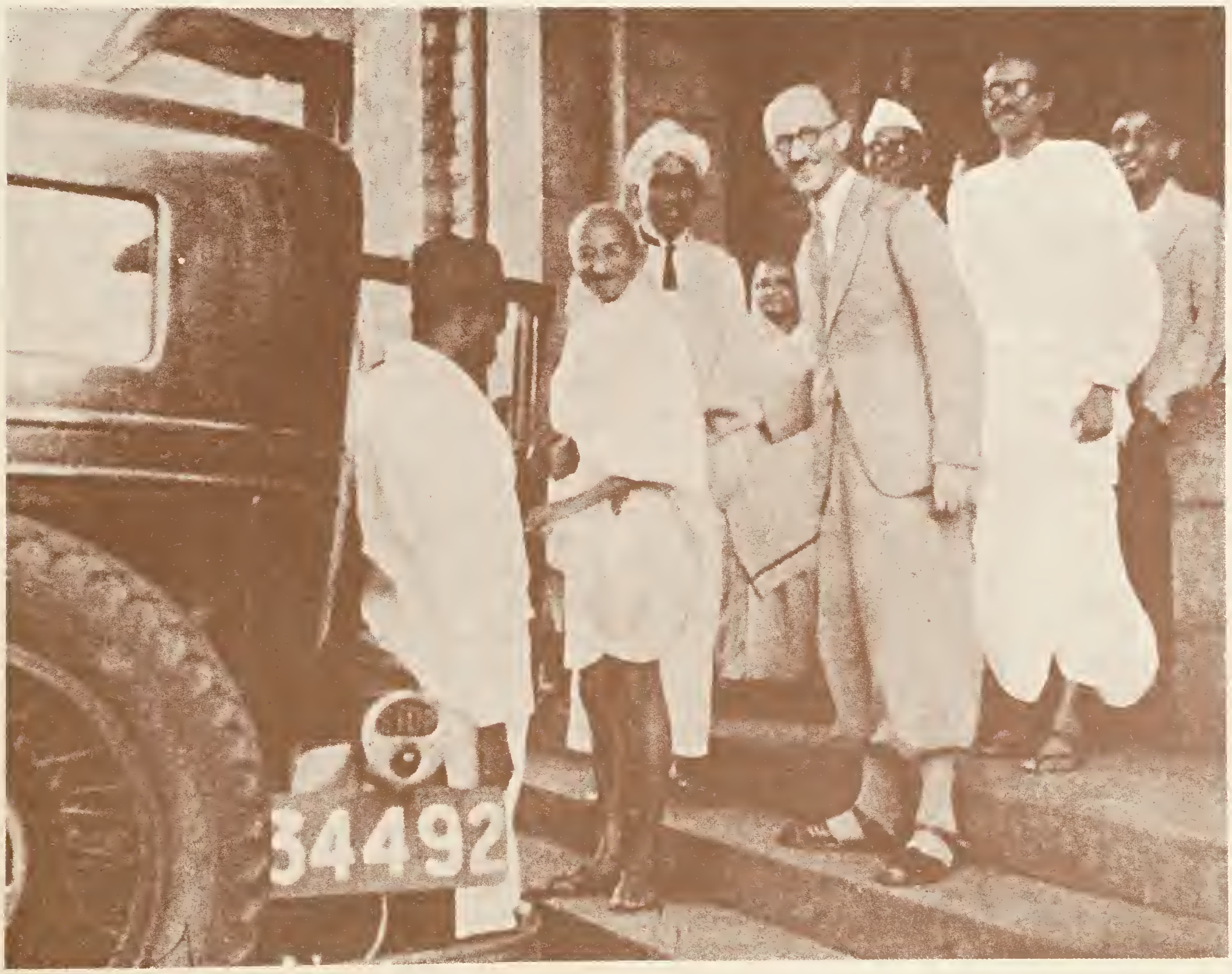
Lady Raman once showed me a copy of a letter a friend of hers had sent her from the United States, a letter written by the Chargé d'affaires of the US in Sweden to the US Secretary of State in Washington reporting on the 1930 Nobel ceremony in which two US citizens had also been awarded the Nobel Prize — Sinclair Lewis for literature and Carl Landsteiner for physiology or medicine. I would like to read out a part of it:

> . . . of the prize winners the day was easily carried however by Sir Venkata Raman the Indian prize winner, who, upon returning to his seat on the platform after receiving his prize from the hand of the King was visibly moved by his emotion and sat with the tears streaming down his face.

Raman confirmed that this was true.

> When the Nobel award was announced I saw it as a personal triumph, an achievement for me and my collaborators — a recognition for a very remarkable discovery, for reaching the goal I had pursued for 7 years. But when I sat in that crowded hall and I saw the sea of western faces surrounding me, and I, the only Indian, in my turban and closed coat, it dawned on me that I was really representing my

Mahatma Gandhi visiting Raman at the Indian Institute of Science



> people and my country. I felt truly humble when I received the prize from King Gustav; it was a moment of great emotion but I could restrain myself. Then I turned round and saw the British Union Jack under which I had been sitting and it was then that I realized that my poor country, India, did not even have a flag of her own — and it was this that triggered off my complete breakdown.

Then continues the letter from the US Chargé d'affaires:

> At the banquet that evening his [Raman's] speech was a masterpiece of eloquence, which called forth tremendous applause from a banquet-weary gathering not noted for their responsiveness. Less appreciative was perhaps the British Minister, who sat one place removed from me, who was forced to listen with equanimity to Sir Venkata Raman's reference, — brief though it was and in passing only, — to the congratulatory telegram which he had received "from his dearest [sic] friend who was now in jail".

It is not difficult to guess who that friend was.

10. Raman the speaker

To the Gandhi Memorial Lecture, an annual feature at his Institute since 1959, Raman attached much importance. He believed that the way to pay homage to a person you revere and love is to give something of yourself — something you yourself can do best. Thus his tributes to the Mahatma, year in and year out, were in the form of popular lectures in science — two fields in which he was an acknowledged master.

I have in my career heard lectures from many many scientists, from India and abroad. But Raman in his heyday was perhaps the best. What made his lectures so gripping? He talked only of those things about which he felt intensely or those things which he understood well or wanted to understand better. He brought out things in their simplest and their most basic elements. He made his audiences feel that they had seen it all too.

His humour was infectious. He made his audiences roar with laughter. After one such "performance" (as he called his popular lectures) he went on about the subject of humour.

> As someone said, the relationship of a joker to a joke must be quick and desultory — as that of a bee to its flowers. He must make a joke and not harp on it. Like a bee approaching a flower he probably can buzz a little – for it is well to announce to a thick-headed world — that a joke is coming or is intended.

11. Raman's style of writing

To illustrate his writing style I shall read a little passage from an essay which describes the influence Euclid had on him.

> Not until many years later did I appreciate the central position of geometry to all natural knowledge. I can give a thousand examples. Every mineral found in Nature, every crystal made by man, every leaf, flower or fruit that we see growing, every living thing from the smallest to the largest that walks on earth, flies in the air or swims in the waters or lives deep down on the ocean floor, speaks aloud of the fundamental role of geometry in Nature. The pages of Euclid are like the opening bars in the Grand Opera of Nature's great drama. They lift the veil and show to our vision a glimpse of the vast world of natural knowledge awaiting study.

In his scientific papers too Raman's style of writing is confident and stately. He is never hurried, neither missing a word nor allowing an unnecessary one to slip in. The *mot juste* is always there. With Raman the style is the man himself.

12. The controversy over lattice dynamics

I shall now briefly touch upon the painful controversy between Raman and Max Born — two physicists who were once great friends. Max Born had written a monumental paper on lattice dynamics. It was a work of art, looked upon with awe by many, carefully preserved as if in a glass casket, untouched by human hands — for decades. No crystal property was ever calculated using it. There was absolutely no interest in lattice dynamics at that time. Then came Raman. He entered the field with a bang and literally opened up the subject. He started a massive experimental programme. In the second-order Raman spectra of crystals recorded by Rasetti and later by RS Krishnan he saw many phenomena yet to be explained. Being the pragmatist he was, he wanted a theory to be useful, a theory from which he could extract numbers.

He disagreed with Born's notion of normal modes expressed in terms of travelling waves and he felt with some justification that Born's cyclic postulate had no physical basis. So he started with standing waves. An ardent student of Rayleigh, he used his master's definition of normal modes and imposed a reasonable condition that he derived and that is almost identical to the well-known Bloch condition in solid state physics. He derived a simple (and what I would *now* describe as a simplistic) form of lattice dynamics. At last he had a theory that could be used. He could now count the number of lattice frequencies in crystals. These were almost identical to those observed in RS Krishnan's excellent Raman spectra of NaCl, diamond, etc. He was able to calculate the actual frequencies using the concept of force constants and nearest-neighbour interaction and again the agreement was almost exact. He computed the specific heats using the idea of Einsteinian oscillators and with no adjustable parameters whatsoever and here again the agreement with experiment was extraordinary. With this success he was convinced that Born was completely in error and so mercilessly attacked Born's theory. Because of his persistent attacks he provoked new interest in lattice dynamics and the Born protagonists broke the hallowed glass casket and looked in – and lo and behold, new physics literally poured out, revealing the innate richness of Born's theory! The concept of singularities emerged (which strangely was also discovered in Raman's laboratory by his student KS Viswanathan), and it was finally shown that Raman's theory was just a small part of the more comprehensive Born theory.

If Raman had presented his papers as a simple physical approach for deriving optical modes or for obtaining the physical properties of crystals, they would have been considered significant or even important at that time. But Raman would not have it that way. He could not see the missing elements of his theory. Rayleigh's definition was right, his derivation of the Bloch's condition was right — but alas it was only valid for travelling waves. Raman had imposed a travelling condition on a standing wave situation. It did explain many important features but it was very limited. Raman had leaned heavily on his intuition, which had never failed him so far from 1904 to 1939, but now it let him down badly. This pattern is not unusual in the history of science — intuition so responsible for a scientist's success often failing him as he grows older. But the greatest sadness and the pity of it was the bitterness this awful controversy created between two old and dear friends.

13. Max Born in India

The story of Max Born in India is an unbelievable one. Like Mahendra Lal Sircar other visionaries appeared who felt that science was the only path to salvation for India. JN Tata was one such and he conceived of the Indian Institute of Science. But the Viceroy, Lord Curzon, felt that this conception was a seditious act and so tried to abort it. The Institute did come into being in Bangalore sometime after JN Tata's death. But with his death the fire went out of the Tatas till it was kindled again, only much later, by the present Tata (JRD). In between, the Tatas leaned heavily on the British. The Director and many in the faculty of the Institute were always British. There was a strong feeling — quite justifiable — that what work was done at the Institute, with the British Resident as Chairman, only subserved British interests. Even so, at the height of the civil disobedience movement in 1933, Sir C.V. Raman was appointed its first Indian Director. Perhaps his British knighthood impressed the Government of India and the Tatas.

Raman however believed in excellence *per se* and was further convinced that if ever India was to make any economic advance it could only be based on such excellence. Says Max Born, "Raman found a sleepy place where very little work was being done by a number of extremely well paid people." Raman went in there like a bull in a china shop. He started improving not only the intellectual but the physical environment. He planted beautiful flowering and avenue trees; the aesthete that he was, he made the Bangalore Institute the garden it is now. He started workshops to make precision instruments — as a necessary activity for building a strong base for experimental research and, for that matter, even industrial research. He started new schools of research; he blazed new trails in physics — in colloid scattering, ultrasonic diffraction, Brillouin scattering, crystal transformation — and put the Institute on the scientific map of the world, some say for the first time. He then identified gaps in knowledge in India and adopted the strategy of trying to recruit to the Institute faculty from among the reputed scientists who were fleeing from the tyranny of Hitler. Could his strategy have worked? In retrospect we know that a similar process of influx of German refugees into the United States improved the quality of science there by orders of magnitude. But unlike the United States India was still a slave nation.

Raman had a long list of subjects that stirred the imagination. Some of these were practical too. Quantum mechanics, radioactivity, crystal chemistry — the

handmaiden of modern materials science, vitamin chemistry, enzymology, and so on.

In his list of people to attract were Max Born, Hevesey of radioactivity fame, VM Goldschmidt (the father of solid state chemistry whom Hitler had insulted and disgraced), Ewald, Kuhn, and a host of others. Many of his list got the Nobel Prize much later, testifying to Raman's discernment. Many of them in fact agreed to come, but finally did not because of what happened to Max Born.

Max Born (and his wife Hedi) came to India first on a short assignment. "We liked Lady Raman right from the beginning" says Born, and "when Raman appeared he looked to Hedi like a prince from the Arabian Nights." Later he says, "Frankly I like Raman very much, in spite of his all-too-human drawbacks; his conceit; his *naiveté*; his wayof bringing himself into the light." Born continues, "He is an excellent physicist and so devoted to the Institute."

Born enjoyed his stay and his lectures were greatly appreciated. Raman decided to offer him a permanent position. Lord Rutherford was appointed Chairman of the Selection Committee, and lo, Born's name led all the rest! In a meeting at the Institute Raman spoke of the extraordinary merits of Born as a scientist, as a teacher and as a human being. Then, unbelievably, a professor at the Institute, an Englishman, spoke in the most derogatory manner about Max Born referring to him as one rejected by his own country, a renegade, and therefore a second-rate scientist, not fit enough to be a member of the faculty of the Indian Institute of Science! All this about the great Max Born. One could have wept — we know Born did.

After this public insult Max Born could not possibly accept Raman's offer, and all the other German professors naturally refused to come. India missed an incredible opportunity, and Raman too lost all hopes of revitalising the Institute. Why did Raman fail? I quote: "The English faculty resented working under an Indian, Raman. They gained the ear of the colonial government who could easily put pressure on the all-too-willing Tata group." And, "Raman, far too conscious of his superiority, made people feel small in his presence" and finally to quote from a letter Born wrote to Lord Rutherford asking him to intervene when all went against Raman: "There is no Indian physicist of the rank of Raman. No man can compare with him in regard to vigour and intensity. This European intensity which Raman exhibited seemed to make many Indians suspicious of him."

It was a battle between excellence and mediocrity, and mediocrity won hands down. The authorities decided to dismiss Raman. He was forced to resign the directorship and only by the intervention of Lord Rutherford could he retain his professorship and so continue to be in India and do scientific research. It is revealing that just a week after these incidents happened Raman wrote a very remarkable scientific paper which was published in *Nature*.

14. What is in a name?

Indian names are sonorous. But often one has to take a deep breath before enunciating them fully. For example, when I say Sudhanshu Kumar Banerjee or Bidhu Bhushan Ray — two outstanding students of Chandrasekhara Venkata Raman — you will see (or hear) what I mean. Raman was clever and contracted his name from Venkataraman to Raman. Raman Effect sounds far better than Venkataraman effect.

At the time Raman was being disgraced in Bangalore one of his friends (Born or Rutherford – I do not know who), thinking that he might like to leave India to lick his wounds, proposed him to the prestigious Zeeman Chair in the Netherlands. Raman was selected but was in a dilemma as he was reluctant to leave his country. Because the name Raman rhymes with many European names and because he had won the Nobel Prize, the City Committee (which had to approve all the university appointments) thought at first that he was of European origin. When they learnt he was an Indian, the appointment was cancelled, saving Raman the trouble of deciding what action to take.

Zachariasen, the doyen of X-ray physicists, told me this story in 1965. When Raman visited Chicago in the twenties as AH Compton's guest, Compton invited him to lunch. Also invited was Dean Gale, who was a specialist in optics and was familiar with Raman's work, but whom Raman had never met. At the Faculty Club, when Gale came in and saw the complexion of the man sitting with Compton he just looked straight through them and walked away. Zachariasen said that although Compton felt immensely ashamed of his countryman's behaviour, he was rather relieved that the incident had passed without Raman noticing it. I discovered later that Raman had, in fact, noticed it, but kept his silence as he did not want to embarrass Compton. Raman said: "As in India, there are many stupid fools in every country. I would like to remember the United States as the country of Jefferson and Franklin, Walt Whitman and Thoreau, Edison and Graham Bell, or my own friends Millikan and Compton."

15. The Indian Academy of Sciences

In 1934 Raman started the Indian Academy of Sciences. His detractors said that he did this to pre-empt the formation of another Academy which was in the offing (later to become the Indian National Sciencc Academy). There may be an element of truth in this accusation. But as Raman asked, "How can Indian science prosper under the tutelage of an Academy which has on its council of 30, about 15 who are Britishers of whom only two or three are fit enough to be even its Fellows?" With the passage of time, and looking at the names of these council members, one can hardly disagree.

In any case the best scientists from all over India and particularly the young ones were elected into his Academy. Raman used his personal prestige and that of the Academy to encourage scientific talent wherever it was found and in whatever field it showed itself.

Distinguished scientists were always at the annual meetings — at Raman's travelling circus, as he called it — which were usually held in university towns. He and his troupe were the greatest salesman science ever had in this country. How many gifted men have admitted that they took to science just because they had heard Raman lecture!

He started and ran many scientific journals. Just before he died he said: "Do not allow the Academy journals to die — for they are sensitive indicators of the quality of science done in the country. They will tell us whether science is really taking root in the country or not."

16. Raman's obsession with science

I do not have the time to elaborate on all his exploits — how at sixty when he retired from the Indian Institute of Science he started the Raman Research Institute; how he lost all his life's savings; and how he went round the country collecting money, saying that our greatest men, Buddha, Sankara and Gandhi, too, were beggars; how the factories he had started sustained his Institute.

Nor have I the time to tell you of how deeply disappointed he was with the way Indian science was going after Independence; how it seemed to him that the administrators of science had no faith in the inner strength of our country and how they looked outside more and more for inspiration; how strongly he felt that the universities which till then had played the role of identifying and generating talent were being denuded and desertified by the exodus of scientists and teachers to better-paid positions in large impersonal governmental laboratories; how he disagreed with the philosophy that expenditure in science was equivalent to progress or growth of science and technology; how in this process quantity was invariably mistaken for quality; and how therefore he became a strong critic of Government and its policy, and so dissociated himself from it by refusing governmental funds for his Institute.

When one hears of all this one may conclude that his major activities were to start and run research institutions and laboratories, train students, get them lucrative positions, establish and publish scientific journals and persuade scientists to publish in them, establish Academies to encourage talented scientists, give popular lectures in schools and colleges to persuade the youth to devote themselves to science, fight anything that he felt was being done to decrease the self-respect and self-reliance of the country. All this he did and with gusto — but all these activities were subsidiary to his one real preoccupation and passion, that of doing science. Pursuit of science was the only reason for his existence, nothing else mattered. From 1905 to 1970, day in and day out he did science. For thirty-five years when his intuition was at its peak his science was almost unmatched. This intuition did begin to decline but not his passion for science. He published 475 papers and wrote five remarkable monographs – a total of 4000 printed pages on topics so varied that one's mind boggles.

It was truly *l'affaire d'amour* with Nature – mostly with sound and light – a prolonged passionate affair lasting sixty-five years.

17. His choice of problems

Raman had a nose for significant problems and he chose them with *élan* whether they were for his own research or for those of his colleagues. I shall give two examples. When young Vikram Sarabhai came to work with him, Raman informed him of the chance observation in Germany that cosmic rays also make imprints of their tracks on photographic plates. Sarabhai said later that Raman exhorted him, "This is the most appropriate technique for our country, perfect the process of making these photographic plates, study cosmic rays at high altitudes using balloons; there may still be a Nobel Prize lurking for you." But it was Cecil Powell of Bristol and not Sarabhai who did pursue this line of research and was in fact awarded the Nobel Prize for his work.

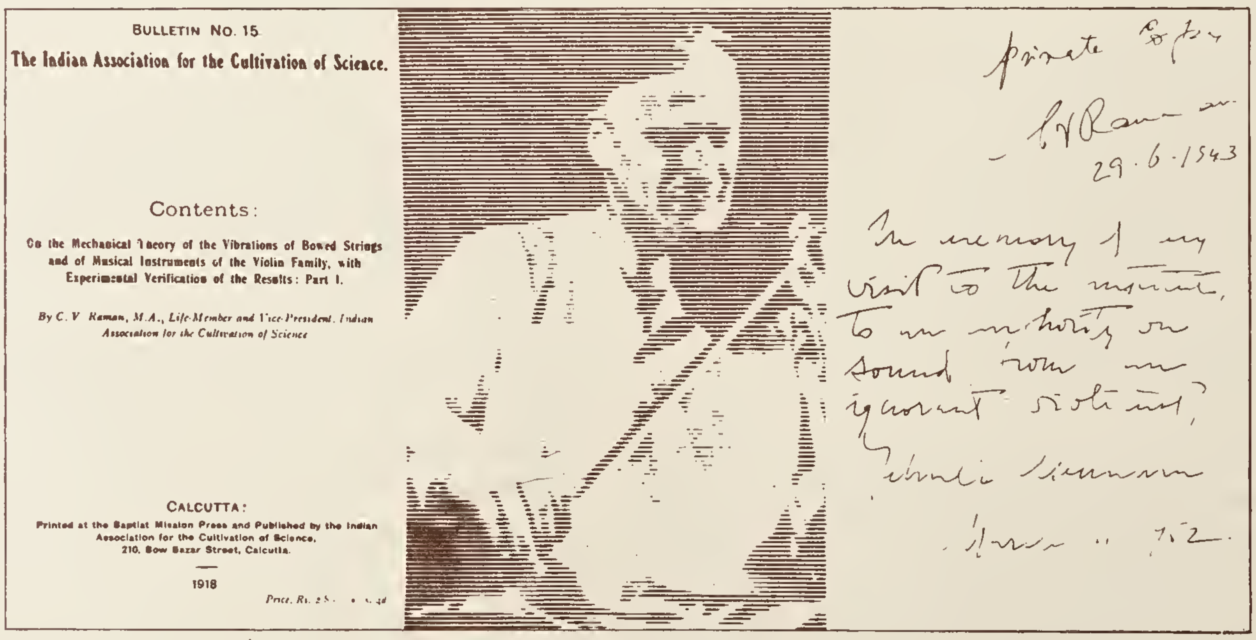
From his mineral collection Raman gave crystals of iolite and amethystine quartz to Pancharatnam, saying, "If you study these, you will surely advance crystal optics, but you may even perceive some strange properties of light itself." As a result Pancharatnam published a series of papers on the generalised theory of the interference of light which have in fact now become part of the standard literature on the subject. In 1954 Pancharatnam also discovered what Michael Berry (one of the most perceptive authorities on wave phenomena) calls the Pancharatnam phase, a property of light which reveals new directions even in purely quantum-mechanical applications.

18. Some of Raman's researches

Some of Raman's researches and discoveries were so outstanding — like the Raman Effect (1928), the Raman–Nath theory (1934–1936), his studies on Brillouin scattering (1933–1940), and the soft mode process (1938–1940) — that they overshadowed many of his other beautiful and significant contributions. Just listing all the scientific problems Raman tackled will take too long. I shall therefore choose only a few — almost at random — to indicate the eye and ear he had for beauty, the concern he had for basic questions, and the range of his scientific interests.

When he listened to the notes of the *ectara* (a single-stringed instrument), commonly used by the poorer itinerant musicians of India, he made a detailed study of it and discovered many unforeseen acoustical properties which led him to design a new type of sonometer! He found that in the Indian *veena* the overtones do not die down rapidly, and that they behave in a manner quite different from those in most plucked stringed instruments. He deduced that it is the curved bridge which endows this class of instruments with the property of producing the normally forbidden harmonics, rendering their sound closest to the human voice. His keen ear detected that the Indian concert drums (the *mridanga* and the *tabla*), unlike most drums of the world, are *not* musically defective. They are in fact capable of producing harmonics (at least five of them) mainly because their ancient designers had centrally loaded the stretched membrane. His *magnum opus* in acoustics was his monograph *On the mechanical theory of bowed strings of the violin family* which is referred to by acousticians even today, seventy-five years after it was written. One can only marvel at his experimental skill in producing remarkable vibration curves of great precision and sharpness much before the triode valve or the condenser microphone were invented. He extended his acoustical studies on whispering galleries to show that the striking beauty of the pearl — the gem that does not require the services of a lapidary — is essentially because it is a leaky, spherical optical whispering gallery.

His pioneering studies on sound produced by impact led him to propound, with rare insight, the mechanism of the breakdown of solids due to impact — a field that he was amongst the first to open up. The renowned polymer chemist Staudinger used Raman's


BULLETIN No. 15

The Indian Association for the Cultivation of Science.

Contents:

On the Mechanical Theory of the Vibrations of Bowed Strings and of Musical Instruments of the Violin Family, with Experimental Verification of the Results: Part I.

By C. V. Raman, M.A., Life-Member and Vice-President, Indian Association for the Cultivation of Science

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1918

Yehudi Menuhin's inscription in Raman's monograph on the violin

phenomenological theory of viscosity to correlate the viscosity of polymer solutions with the states of polymerisation of the molecules. Raman was amongst the earliest to suggest that optical birefringence and magnetic anisotropy should be used to predict (or to verify) the arrangement of molecules in a crystal, a procedure followed so ably by his students S Bhagavantam and KS Krishnan.

The obsession he had for the beauty of the haloes he saw surrounding the sun and the moon when a thin cloud (of water droplets) came in front of them resulted in his discovery of the speckle phenomenon as early as 1919. It led to his theory of X-ray diffraction of liquids (with KR Ramanathan), the calculation of the X-ray structure factor of an atom, and the classical derivation of the Compton Effect formula. It should be noted that X-ray topography was also discovered in his laboratory (by GN Ramachandran) during studies on the imperfections in diamond.

He discovered and explained one of the strangest cases of image formation, that of a sharp image forming not at one point but continuously on all points on a line when light emerges after travelling along a singular direction in a birefringent crystal. He propounded the geometric theory of Fresnel diffraction, in which the intricate diffraction pattern could be simply deduced as due to the interference of a few rays emanating from edges and poles whose positions are easily identifiable. Only in recent times has optical theory been rewritten to make these rays meaningful in such situations, thus catching up with Raman's intuition three decades earlier. The first qualitative statement of the presently accepted theory of the scintillation of stars, that it is an effect created by the random corrugation, due to the density variation in the atmosphere, of the plane wavefront arriving from a distant star, was given by Raman. He claimed to have made a most intriguing observation of a second type of twinkling of stars, due to the statistics of photons striking the retina. He made detailed studies of the not-too-well-known property of the unaided eye of detecting polarised light (as bees seem to do).

The similarity between periodic precipitates in nature and wave phenomena had been noticed previously. But Raman (with K Subba Ramaiah) gave substance to this analogy by actually detecting in these precipitates the existence of phase relationships in the form of interference and diffraction effects. Raman's study of the scattering of light brought out many important prescient conjectures much ahead of their time. He suspected the periodic compositional segregation in minerals corresponding to what are known today as modulated structures. In the very first paper on the subject Raman argued that the large Rayleigh-like scattering of light in complex glasses must be due to sizeable compositional variations, marking the beginning of a powerful way of probing a class of systems and phenomena not fully understood yet. Finally Raman considered protein molecules in solution, and probably for the first time, the protein was thought of as a thermodynamic system and not as particles like dust.

19. Later extensions of Raman's researches

Many of Raman's researches had a much wider application to many other situations. For example the mathematics needed in the multiple-beam dynamical theory of electron diffraction is just that introduced by Raman and Nath twenty years earlier to deal with the diffraction of light by ultrasonic waves.

The remarkable paper by Raman and Pancharatnam on mirages, which brings out the interplay of geometrical optics with wave optics, is another case in point. The solution to the wave equation showed the wave to be made up of three sheets, joined at the cusp, which travel along the caustic surface in which three images are to be expected. The principles elucidated by Raman and Pancharatnam for terrestrial mirages were reintroduced many years later for cosmic mirages, the formation of multiple images by distant quasars caused by the gravitational bending of light by intervening masses. Efforts to model these "gravitational lenses" also give a prominent role to an odd number of images and the cusped wavefronts moving along caustic surfaces. In fact the Raman–Pancharatnam paper will therefore be remembered not only for the wave-optical treatment of the image but also for the clarification of the associated geometric-optical limit.

20. His last days

On October 2nd 1970 Raman gave his last Gandhi Memorial Lecture. For the first and only time in his life he asked of his large audience permission to answer questions sitting down! At the end of October he collapsed in his laboratory, the valves of his heart having given way. He was moved to hospital and was expected to die within four hours. He survived and refused to stay in hospital as he preferred to die in his Institute home, surrounded by his flowers. When he asked and was told that there was little chance that he could lead a normal life, he refused

any medication since he would not care to live in any way other than that in which he had always done. Two days before his death he talked about his hopes for the future of his Institute. He held a meeting of the Board of Management of the Institute, conducted the proceedings from his bed, and dictated the minutes of the meeting, introducing in it the sentence, "Since Sir C.V. Raman was not in a position to hold a pen he requested that the minutes be taken as signed by him." He even instructed his secretary to make sure that the travelling allowance was paid to the members.

He died peacefully on the morning of November 21 1970. There was a simple, clean cremation with no mumbo-jumbo in the gardens of his Institute, as he had desired.

21. Uniqueness of Raman

What were the characteristic features that set Raman apart from most others as a scientist and a man?

I have never seen anyone who enjoyed science so much. The sheer joy of seeing things and doing science filled him with exuberance and excitement. He had an incredible zest for life. He enjoyed his food, his jokes, his travel, his story books and novels, his fights and quarrels. Yet the enjoyment he had for his science was something apart. In this pursuit it was as if his ego disappeared completely in the presence of effulgent Nature. Yes, he was truly lost in the wonder and beauty of what he was trying to comprehend.

I have never seen him in fear — he was a man truly unafraid. He feared nothing, no situation, no one and no authority, and in this respect he was very different from those around him.

We are celebrating the centennial of his birth. The question we should ask is, "Is Raman relevant today?" Once, after he had made a very pungent attack on the manner in which universities were being neglected and despoiled, I asked him whether he had not been too harsh. This provoked a long discourse on the need to express one's opinion with honesty. In short he said: "Even a man of sensitivity and imagination can become bound and unfree when he has to falsify his feelings. If he forces himself to say that he likes what he dislikes and that he believes what he does not believe then he will have to pay the price in that his spontaneous and his creative faculties will dry up."

In his day, Raman was amongst the very few who stood up and spoke their mind. Today we have a very much larger number of scientists in this country, but one scarcely hears any of them speaking out.

The main purpose of celebrating a great event like the Raman centennial should be to derive inspiration from it.

Young scientists, like so many of you here, must learn to enjoy doing science as Raman did and to stand up to authority and speak your mind. Only then will the future of science in this country be assured.

C.V. RAMAN and the German connection*

Chandrasekhara Venkata Raman (C.V. Raman) is one of the legends of Indian science. The discovery he made in 1928, the Raman effect, for which he was awarded the coveted Nobel Prize, has never been surpassed in quality by any other made in India. His incredible career evokes many questions. What prompted him to do science at such a tender age? Where did he acquire such a passion for Nature, which provided him the problems for his famous discoveries? Seeking answers to such questions I found there were many connections between Raman and Germany.

Raman was born in 1888 of poor parents; even in his teens he had an unusual yearning to understand the

* Article written on the occasion of the Silver Jubilee of Max Mueller Bhavan.

Niels Bohr and Raman

nature of things. He started experimental science in his college at Madras at the age of 15. Since research was not yet a profession in India he appeared for and passed the Financial Civil Service Examination and at the age of 18 was appointed the youngest Assistant Accountant-General in the Government of India. While he did his office work with diligence he pursued science "before and after office hours" mainly at a place he had discovered in Calcutta — the Indian Association for the Cultivation of Science (IACS) — which was a haven to him.

His scientific investigations attracted the attention of scientists both in and outside India. Sir Asutosh Mookerjee, the Vice-Chancellor of the Calcutta University, known for encouraging and gathering exceptional talent in the country, was so struck by Raman's genius that he offered him a Chair of Physics. Raman accepted it in 1917 although he suffered considerable financial loss. He attracted a large number of students and IACS became a hive of scientific activity. It was here that he also made the discovery which made him and India famous.

Later, in 1933, he left Calcutta to become the Director of the Indian Institute of Science (IISc), Bangalore. On his formal retirement from IISc, he established the Raman Research Institute in 1948. He trained scores of students, published hundreds of scientific papers and monographs, founded the Indian Academy of Sciences in 1934, started and ran many scientific journals, and carried on his personal research right up to his death in 1970. During this remarkable career Raman made many major scientific discoveries in such fields as acoustics, ultrasonics, optics, magnetism, X-rays and crystal physics. His interests were wide, from astronomy and meteorology to physiology.

To a country that was fighting for independence and trying to establish its identity, he became a symbol of its intellectual resurgence, to both young and old, because of the impact he made on the rest of the world. When he died in 1970, the President of India Dr. S Radhakrishnan said:

> C.V. Raman was a great teacher. His knowledge was not confined to the physical sciences. In this over-specialized world his breadth of knowledge was remarkable. He combined the highest intellectual integrity with a winning warmth of heart.... He was our most illustrious scientist who continued for many years to guide the scientific progress of India.

Raman and Helmholtz

Raman had never been outside India till 1921. Yet what prompted him to pursue, with almost inexplicable vigour, modern science, which is considered by many to be a western implant? Apart from his native talent, did anyone inspire him? I discovered recently a transcript of a speech by Raman in a book entitled "The books that influenced me" which gave one answer to this question.

Just as Raman dominated the Indian scientific scene in the first half of the twentieth century, Hermann von Helmholtz bestrode German science during the mid-nineteeth century. His wide-ranging and exact work brought Germany to the forefront of world attention, a position she was to enjoy well into the twentieth century. Helmholtz was an inspiration to many, including his most distinguished student Heinrich Hertz, the discoverer of radio waves. There is no doubt that Raman too was inspired by Helmholtz. So great was this impact that young Raman actually put von Helmholtz on par with the great Newton. He said:

> Speaking of the modern world, the supremest figure, in my judgement, is that of Hermann von Helmholtz. In the range and the depth of his knowledge, in the clearness and the profundity of his scientific vision, he easily transcended all other names I could mention, even including Isaac Newton. Rightly he has been described as the intellectual colossus of the nineteenth century. It was my great good fortune, while still a student at college, to have possessed a copy of an English translation of his great work *The sensations of tone*. As is well known this was one of Helmholtz's masterpieces. It treats the subjects of music and musical instruments not only with profound knowledge and insight but also with extreme clarity of language and expression. I discovered the book myself and read it with the keenest interest and attention.
>
> It can be said without exaggeration that it profoundly influenced my intellectual outlook. For the first time I understood, from its perusal, what scientific research really meant, and how it could be undertaken. I also gathered from it a variety of problems which were later to occupy my attention and keep me busy for many years.

Raman's researches on the musical instruments of India

It is said that orientalists owe the composer Mendelssohn much, as he dissuaded Max Mueller from

devoting himself to his first love — music! Max Mueller therefore turned to linguistics with his heart and soul and as a result could expound the culture of the east to the rest of the world. I think we owe it to Helmholtz that Raman took up the scientific study of Indian musical instruments and brought out some of the most unexpected aspects of their design. It was Raman's view that although music played an important role in the cultural life of ancient India, the material now available for writing its history is all too meagre. A better method of probing into the development of musical knowledge in ancient India would therefore be a scientific study of the musical instruments which have been handed down as heirlooms for untold generations.

The work of Raman on the musical drums of India is epoch-making and reveals the acoustical knowledge of the ancient Hindus—which is the title of a paper published by Raman. It was Pythagoras who first formulated what makes a sound seem musical to the human ear. If the string of an instrument is plucked, struck or bowed, it not only emits a note having a fundamental frequency, but also produces higher notes. If these overtones are in the ratio of the natural numbers (2,3,4, etc to the fundamental), the effect is musical, otherwise it is discordant or unpleasant. Scientifically it is well known that percussion instruments as a class can only produce inharmonic overtones and are therefore in a sense only noise makers. Raman's ear however detected that the Indian percussion instruments stand in an entirely different category in that they produce truly musical sounds. He showed that this was achieved by the partial loading of the drum membrane with a firmly adherent but flexible paste. As a consequence, the Indian *mridangam* and *tabla* produce a succession of musically harmonic overtones in the same way as any stringed instrument.

The famed stringed instruments of India, the *veena* and the *tanpura,* are of undoubted antiquity and revered as a gift of the gods because their sound is considered closest to the human voice. Their tone exhibits a quality much superior to most "plucked" instruments. Raman made the surprising discovery that certain overtones, which, according to known acoustical principles, should be entirely absent, sing out with great intensity in these instruments. He showed that the violation of what is called the Young–Helmholtz law is due to the curved bridge which the ancient Hindus had cunningly fashioned so that the *veena* (and the *tanpura*) could produce sounds richer in quality, worthy of Saraswati, the goddess of music whose favourite instrument it was.

Raman's acoustical studies were not confined to Indian musical instruments and they extended also to other western ones. While his wife was an accomplished veena player, it is hardly known that Raman himself was once a reasonably competent violin player. His mathematical theory of the bowed string and its experimental verification, his theory of how the impact of the hammer produces the exquisite vibration in the pianoforte and his demonstration of the peculiar wolf note produced by the violin and cello were all accepted and recognized by the experts of the musico-acoustical world. As a consequence he was invited to contribute to the *Handbuch der Physik* (published by Springer-Verlag). This article entitled "Musikinstrumente und ihre Klange" (musical instruments and their tones) published in this prestigious German encyclopaedia of physics is considered an

Raman with scientists in a tourist bus

authoritative one on this subject. Raman wrote the article in English and it was translated into German. My attempts to get the original English version that Raman wrote for publication in *The Scientific Papers of C.V. Raman* were unsuccessful.

In the talk referred to earlier about Helmholtz, Raman greatly regretted that he could not read the other classic of Helmholtz — *The physiology of vision* — "as it has not been translated into the English language". In the twenties Raman could read with ease scientific monographs written in German and he could even manage to speak the language (at least to non-Germans!). When he first went to the USSR, German was the only language of communication. The story goes that in Leningrad, Raman was shown by a professor a recent experiment he had performed on anomalous dispersion. On seeing it Raman exclaimed:

> "Das ist sehr Schon. Aber ist es nicht Rozhdestvenskii–Experiment?" (This is very beautiful; but is it not the Rozhdestvenskii experiment?).

To which the Professor replied:

> "Ja. Ich bin Rozhdestvenskii." (Yes. I am Rozhdestvenskii.)

The blue of the sea

On the first journey to Europe in 1921 Raman was struck by the incredible beauty of the blue of the Mediterranean sea and saw in it a vision of a vast world of knowledge awaiting study. By performing an elegant but crucial experiment on board the ship (with optical components he had with him) he was able to disprove a conjecture made by Lord Rayleigh, that the blue of the oceans was due to the reflection of the blue skies in the waters. In 1922 he wrote the famous monograph *Molecular diffraction of light.*

There are two aspects of light. One is that it consists of electromagnetic oscillations (Maxwell and Hertz). The other is the complementary view propagated by two of the greatest scientists of this era, Max Planck and Albert Einstein, that it consists of particles (quanta) and that certain observations like the photoelectric effect — incidentally discovered by Hertz — can only be explained on this basis. In the monograph referred to above, Raman says that if scattering of light is considered as a collision of a light quantum with a molecule many concepts derived from the classical wave theory may be violated.

Raman's discovery and the Kramers – Heisenberg theory

For the next six years Raman drove himself and his students to see whether these violations could be discovered. He finally succeeded on 28 February 1928. It was shown that the light quantum and the molecule do exchange energy which manifests itself as a change in the colour of the scattered light. (Sometimes the light quantum gave a part of its energy to the molecule to excite it and the quantum was scattered with diminished energy and at other times it was scattered with greater energy by acquiring some from the vibrating or rotating molecule.)

Historically, A Smekal in 1923 published a note in the journal *Naturwissenschaften* considering the quantitative aspects of the collision process that Raman thought of in his *Molecular diffraction of light.* Unfortunately, this paper was not noticed by experimental physicists including Raman and his group. Two years later, in 1925, Kramers and Heisenberg (two great names in European physics) developed Smekal's idea in a paper which is now considered one of the classics in physics. (It may be noted that Heisenberg was to invent quantum mechanics, some of it based on this paper, and to revolutionize physics thereby.) Their paper contained many beautiful but complex ideas, but again their experimental implications were not obvious nor were they made clear in the paper. However, Raman seems to have perceived their import. In fact, when hot on the trail (three weeks before the actual discovery of the Raman effect), K S Krishnan, the major collaborator of Raman, writes in his diary:

> February 7th Tuesday: Professor [Raman] came to the house—about 9.00 p.m.—and called for me.

KS Krishnan, A Sommerfeld and C.V. Raman

> We [Venkateswaran and Krishnan] went down. We found him very excited and he had come to tell me that what we had observed that morning must be the Kramers–Heisenberg process we had been looking for all these days. We, therefore, agreed to call the effect *Modified Scattering.*

The visit of Arnold Sommerfeld to Raman's laboratory

Sommerfeld, the renowned German physicist, author of the classic *Atombau und Spectralinien,* and who shaped theoretical physics in Germany by the style of his lectures and his remarkable qualities as a teacher, decided to go to the United States through the eastern route (via India). He was

> especially attracted by the wonderful land of India because of its exotic buildings, fantastic religions with their philosophical systems; and also because it was in this ancient land that during the last few years strong shoots of modern physics had grown by which India suddenly emerged in competition in research as an equal partner with her European and American sisters.

About this it is said:

> Sommerfeld was thinking of the spectroscopic effect discovered by Raman which like no other discovery attracted attention and enthusiastic cooperation all over the world.

When Raman heard of Sommerfeld's intention to take the eastern route he sent a telegram (11 February 1928):

> Calcutta University inviting you, lecture honorarium thousand rupees. Kindly wire date arrival India.

As soon as Sommerfeld arrived in India (as is not unusual with foreigners!) he took ill and spent two weeks in a hospital in Bangalore. On 4 October 1928 he arrived in Calcutta and on the same day visited Raman's institute (IACS). Raman showed how using light and a small spherical ball he was able to verify some of the theories of Sommerfeld on the propagation of radio waves round the Earth! Wrote Sommerfeld:

> Everything in the institute very good; but bathrooms terrible!

Sommerfeld's visit to India was, in my view, very significant as he was the first discriminating scientist to come to Raman's laboratory and to see the demonstration of the new discovery. There were some who have even later expressed some scepticism as to whether Raman could have observed his effect visually as the intensity of the Raman scattering would be only a hundred millionth of that of the incident light. They could not imagine the power of sunlight in India which was why Raman chose it for his studies nor did they reckon with the ingenuity that is evoked when a man of genius is short of funds and equipment!

On 6 October, Sommerfeld "eventually saw the Raman effect visually...." On Sunday, 7 October, he heard "a wonderful lecture by Raman—also that the rotations of molecules can be seen (unresolved) as the modified radiation" and on subsequent days "saw the blue-green in an ice block—obviously modified scattering". Indeed, so convinced was Sommerfeld of the reality of the Raman effect, that he proposed Raman as a candidate for the Nobel Prize. There were at least 10 others who also proposed his name for the Nobel Prize.

Sommerfeld after a serious conversation with Raman comments critically on India's economic and political conditions and her difficult relations with Great Britain. He left India

> with deepest affection for the highly gifted but unhappy nation, with sincere gratitude for many acts of friendliness and honours bestowed on him.

Sommerfeld and Raman became very good friends. On his way back from receiving the Nobel Prize in 1930 Raman visited Sommerfeld in Munich. He was received with great joy:

> We welcome our guest not only as a successful scientist and discoverer but also as a representative of the age-old and now rejuvenated culture of the

The Ramans and the Borns with students, IISc

> orient which trustfully cooperates with the occidental culture and strives for the same ends.

It is not so well known that S Chandrasekhar, the astrophysicist (also a Nobel Prize winner), when just 18 years old, met Sommerfeld in Madras during his 1928 visit to India. They discussed the new developments made by Sommerfeld on the theory of metals where he had used Fermi-Dirac statistics. Chandrasekhar went on to extend this to the case of stars which led to one of his important discoveries.

Among the other visitors to the IACS were von Karman in the summer of 1928 and Heisenberg (1929) when he was not yet 28. Unfortunately, I have not been able to get authentic accounts of these visits.

The Raman effect – Pringsheim

The possibility of the existence of the effect discovered by Raman was obviously inherent in the Kramers–Heisenberg paper and in quantum mechanics. As Born says in 1928, just six months after the discovery:

> Raman's discovery is predicted in its entirety by quantum mechanics and could be thought of as a proof for the same.

Then one can ask whether a dozen distinguished men of science proposed Raman to the Nobel Prize just because he found a proof for quantum mechanics. The answer is a definite no. One thing is quite clear – that the implied prediction was obscure even to the theorists and definitely so to the experimenters at that time. The discovery did come as a surprise to everyone. We see an element of this in what Einstein said:

> C.V. Raman was the first to recognize and demonstrate that the energy of a photon can undergo partial transformation within matter. I still recall vividly the deep impression that this discovery made on all of us....

In August 1928, Prof. Peter Pringsheim of the Berlin University published a paper in *Naturwissenschaften* which reported a detailed study (done with the proverbial German thoroughness) of the various then known scattering processes and concluded:

> What has been discovered by Raman is an entirely new phenomenon worthy of being designated "The Raman effect" and the spectrum of new lines associated with it as "The Raman Spectrum"....
>
> One can state without doubt that through his discovery Raman has opened up a vast and completely new field of spectroscopy.

This was possibly the reason why the Raman effect was so enthusiastically welcomed and commended by the leaders of science.

Laue aufnahmen or Laue photographs

The results coming out of Raman's laboratories were so profuse that he needed journals near at hand to publish all of them. In his early days in Calcutta he founded the *Proceedings of the Indian Association for the Cultivation of Science* (1917) and later the *Indian Journal of Physics* (1926). When he moved to Bangalore, he started the *Proceedings of the Indian Academy of Sciences* (1934). He has been closely connected with *Current Science* since its founding in 1932. All these journals are still doing well.

One of the greatest discoveries of modern physics was the diffraction of X-rays by crystals by Max von Laue. When *Current Science* decided to bring out a special number in 1937 to commemorate the silver jubilee of this discovery it was a collaborative effort between India and Germany. Dr Adolf Berliner, the editor of *Naturwissenschaften,* and Prof. Max Born took special interest in this issue and used their personal influence with their friends to get special contributions. The result was that a galaxy of scientists sent in articles—among the authors were Laue himself (Germany), William and Lawrence Bragg (UK) who were responsible for so much development of the X-ray crystal structures of inorganic, organic, mineral and metallic materials, Ewald (Germany/US) who was associated with X-ray crystallography even before its discovery and has done so much for its growth, Manne Siegbahn (Sweden) who made X-ray spectroscopy a precise and quantitative field, Linus Pauling (US) who made the remarkable connection between X-ray structures in chemistry and biology, Hermann Mark (Germany/US) who started as an X-ray physicist but did pioneering work on polymers and J A Prins (Germany) who elevated the qualitative theory of X-ray diffraction of liquids developed by Raman and his school to a precise quantitative one.

In his introduction, Raman thanks these leading authorities in X-ray physics for their contributions and pays tribute to two outstanding experimental discoveries made in Germany:

> Students of optics recognize in Prof. Laue a great exponent of their science.... While the work of Hertz opened up the possibility of communication

with *distant space,* Laue's work brought the submicroscopic world within the range of direct observation.

Laue (in 1912) discovered that when an X-ray beam is diffracted by a crystal, the geometric diffraction pattern can be registered on a photographic plate. Such patterns have been called by generations of crystallographers Laue aufnahmen — Laue photographs.

A meeting was held in 1948 in Boston (USA) when a large number of scientists of the world gathered to decide the establishment of an International Union of Crystallography. On one of the days many scientists were relaxing at a beach near Boston. Amongst those were some well-known ones, von Laue, Lawrence Bragg, Paul Ewald, Raman, Patterson, Hermann Mark, JD Bernal and others. A young lady with a camera rushed to get a photograph of von Laue wearing very brief swimming trunks. Seeing this Raman quipped to Ewald "She is trying to get the real Laue aufnahmen". Paul Ewald was so impressed with this spontaneous pun that he related this to many (including to me 6 years later when I was with him at Brooklyn Polytechnic).

The Indian Institute of Science

In 1933 Raman was appointed Director of the Indian Institute of Science (IISc). This Institute was set up in 1909 with the main objective of pursuing original research and providing advanced training in science and engineering. To JN Tata, the visionary, such an institution was to be the primary base for the intellectual rejuvenation and modernization of India. But to Lord Curzon, the then Viceroy of India, this was a seditious step against the British Raj and so he opposed its establishment. Nevertheless, five years after Tata's death, IISc was established, and that too in Bangalore because of the farsightedness of the Maharajah and the Government of Mysore who offered it nearly 150 hectares of land and many other facilities.

The Directors of the Institute (till Raman's appointment) were always British and so were most of the earlier faculty. Some felt that under the tutelage of the British "Resident" of Mysore State, IISc was subserving the interest of Great Britain, and that even the starting of the General Chemistry and Electrical Technology Departments was connected with the running of the British-owned Kolar Gold Fields.

But such is the irresistible nature of truth that all it asks and all it wants is the liberty of appearing. What Thomas Paine said of truth is equally applicable to education. The effect of research and education "appearing" at IISc had a tremendous effect on the country. Nationalists, however, were dissatisfied with the "performance" of the Institute – that in spite of large sums of money spent neither did the Institute catalyse industrial growth nor did any outstanding scientific discoveries of which India could be proud, come out.

When Raman was to move to Bangalore it was said:

> At present Calcutta may be regarded the centre of scientific research in India. With the transference to Bangalore of one of the leading investigators, Calcutta will have to guard its laurels.

Raman's invitation to German professors

The money spent on science in Calcutta was paltry compared to that spent at the Institute. Raman felt strongly (rightly or wrongly) that research and advanced education can be the foundation for any economic advancement only if there was excellence of the highest order. So Raman tried many strategies for bringing this about at IISc.

The first was to improve the surroundings (not just the houses of the director and the professors) by planting beautiful flowering trees—and in this he was aided by Sir Mirza Ismail, the Diwan of Mysore, and Mr Krumbeigel, the Chief Horticulturist of Lal Bagh.

The second was to set up a central workshop to make instruments (for it was Raman's view that no real progress in science can be made using *only* imported instruments). Precision instruments must be fabricated inside the country.

The third was to set an example of doing quality research. With a team of talented students he (again) blazed new trails in many fields—ultrasonic diffraction, Brillouin scattering, colloid optics, spectroscopic and optical properties of crystals, crystal transformations, X-ray topography and scattering, etc. and put IISc on the scientific map of the world (some say for the first time in its 25 years of existence).

The final method was to fill important gaps in knowledge by recruiting outstanding faculty; Raman had a long list of subjects—some of these were: quantum mechanics (which was revolutionising physics); radioactivity (which was setting the pace in inorganic and biological chemistry); crystal chemistry (which was the

basis for the development of modern materials so essential for India); vitamin and enzyme chemistry (which was making big waves in organic and biochemistry). Raman felt that basic research in these fields will generate applications which would be important for India's development.

It was at this time that many reputed scientists were fleeing Germany to escape the tyranny of Adolf Hitler—and Raman wanted to invite them to India:

> I was not much in favour of young Indians going abroad to be initiated into scientific research. For if they are trained in a completely alien atmosphere not available in India the training may not prove useful. But if savants seeking a country to adopt are provided with a home we could start a great scientific movement.

It appeared to be an excellent idea as witness the renaissance of science in the United States which took place by the same process that Raman tried to adopt for India.

Raman first wrote to Schrödinger, the discoverer of wave mechanics, the physicist-philosopher and author of *The Meaning of Life*. He replied saying that Raman's offer reached him after he had received and accepted another from Dublin, Ireland (although Raman's letter was posted earlier). Thus he has unfortunately "to miss the opportunity of being in the land of Upanishads".

George von Hevesy of the University of Freiburg, a pioneer in the use of radioactive tracers to follow chemical reactions and the movement of chemicals in human tissue, actually accepted the offer but did not come because of the later events related below.

For crystal chemistry VM Goldschmidt, perhaps the greatest authority in this field, was invited. He too accepted the offer but did not come probably for the same reasons.

Raman had many names on his list, both foreign and Indian, and it is a commentary on his choice that many of them (including Hevesy and Born) received the Nobel Prize many years later.

The visit of Max Born

Max Born was among the most outstanding theoretical physicists of this century. He developed the theory of atomic structure, worked on the early versions of the quantum theory (Bohr–Sommerfeld) and saw it blossom into quantum mechanics in the hands of Heisenberg.

Raman first requested Born to suggest the name of a young theoretical physicist for an appointment at IISc but later invited Born himself to spend six months to lecture there. Born and Mrs (Hedi) Born arrived in India in autumn 1935. Born had this to say of his first impressions:

> We liked Lady Raman right from the beginning. When Raman appeared later we were fascinated by his appearance and talk. To Hedi he looked, in his Indian dress and turban, like a prince from *The Arabian Nights*.

Max Born enjoyed his stay and his lectures were appreciated widely. To Lord Rutherford he wrote saying:

> I must frankly say I like him [Raman] very much, in spite of his all too human drawbacks, his conceit and his naivete and therefore his disarming way of bringing himself into the light. I do not take these too seriously as I am finding (on the other hand) a genuine devotion to his work and to the Institute. He is an excellent physicist, full of optimism and activity and besides being interested in everything in the world.

Born interacted not only with Raman but also his students and all seem to have enjoyed it thoroughly. One of his student collaborators wrote of Born:

> It is amazing to speculate how profoundly a great scientific mind can influence those coming in contact.... A most eminent physicist alike in the depth of mathematical power... a teacher whose encouragement and kindness to his students is unparalleled.

And Lady Raman looked after their other activities. Born said:

> Life was pleasant for us; Hedi enjoyed it even more than myself. She met a Swami of the Ramakrishna Order and they became great friends. He told her that she had been an Indian woman in her previous incarnation because she understood Indian spiritual life so well.

So Raman decided to offer a permanent position to Max Born at the Institute. A selection committee was

A discussion on board a ship

constituted and at Raman's suggestion Lord Rutherford was made a member (Chairman?). The latter had no difficulty in putting Born's name first among those recommended for selection. Rutherford conveyed this information to Born who decided to accept the offer:

> While we would have liked to have had your services in Cambridge, I feel that the new position is not only very much better paid, but offers you an opportunity of influencing science in India. In this way I think you can exert a much wider personal influence for good than if you remained in Cambridge where you are one of a number and where possibly missionary work in the scientific field is not so important. Altogether, I feel you have made a wise decision.

All seemed to have been settled but.... At the Council where this decision was to be ratified Raman spoke of the extraordinary merits of Born as a scientist, as a teacher, and as a human being. Then something quite unbelievable actually happened. An engineering professor from England who was rejected for an academic position even in England and whose name means nothing today even at IISc, spoke in the most derogatory fashion about Born—referring to him as a second-rater who had been driven out of his own country and one not good enough to be a member of the faculty of the Indian Institute of Science!

After this public insult, of course, Born felt he could no longer accept Raman's offer and Raman too lost all hopes of rejuvenating the Institute in such a hostile atmosphere.

Why did Raman fail so miserably? There are many views expressed in this connection, some of which I quote. Born himself said:

> Raman came to the Institute with the idea of making it a centre of science of international standard. What he found was a quiet sleepy place where little work was done by a number of well-paid people.... Raman's speeding up of the entire pace of the Institute was bound to look like criticism of the former management. He made the heavy [sic] mistake in not waiting for a year or two before starting actual reforms.
>
> Raman was obviously surrounded by people both British and Indian who largely looked upon IISc as a source of sinecure positions.
>
> Some of the English faculty resented working under Raman — an Indian — an experience they never had before.
>
> The faculty members had gained the ear of the colonial Government which agreed to put pressure on the Tata family.
>
> All changes made by Raman provoked resentment and many felt that physics was in the process of becoming a dominant feature of the Institute.
>
> Raman, far too conscious of his own superiority, made other people feel small in his presence.
>
> Raman with an astute mind and sharp tongue seemed to provoke resentment and tension round him.
>
> There is no Indian physicist of the rank of Raman. No man can compare with him in regard to vigour or intensity. This European intensity which Raman exhibited to a marked degree seemed to make many Indians suspicious of him.

Everything he tried to do was considered wrong and he had to resign his directorship (but retained his professorship at the Institute). It is a matter of great regret to many that Raman and Born who were such great friends fell out much later on a scientific issue. It is Born's view

that the above regrettable incident rankled in Raman's mind which probably led to this unfortunate rupture.

The Raman Research Institute

Raman retired as Professor from IISc in 1948. He wanted to start a small institute for himself (the Raman Research Institute) where he could retire and "enjoy" doing science with a few collaborators. This he hoped to do with his life's savings; but it so happened that he lost most of his savings (including the Nobel Prize money) in a "South Sea Bubble"–like investment. Undaunted, he proceeded and we see yet another European connection. He knew that while in most countries incandescent lamps were the rule, there were others in the East which still used kerosene and other lanterns and where lighting of streets in many cities was still done with gas (for example, Calcutta and cities in the Malay Peninsula). With the aid of a student with a chemistry background he launched courageously into setting up a Welsbach mantle factory. Welsbach (1858–1929) discovered that a fabric soaked in thorium nitrate and cerium nitrate (both chemicals available in India) when heated glows with great brilliance. (Some of Raman's researches drew his attention to this fact.) The product from Raman's factory sold well, and the dividends from this venture were substantial. In fact they were sufficient to support his Institute and keep it independent at a time when he decided, for good reasons, not to accept even marginal support from Government.

The growth and the blossoming of the Raman Research Institute is another story.

Krishnaraja Wodeyar, the Maharaja of Mysore, a patron of arts and science, who gifted the land for the Raman Institute

RESEARCH WITH STYLE: The story of Raman's study of Light Scattering*

Introduction

To those of us who knew C.V. Raman well, what struck us most was his intense love of and preoccupation with Nature. In one of his lectures he said†:

> The face of Nature as presented to us is infinitely varied; but to those who love her, it is ever beautiful and interesting. The blue of the sky, the glories of sunrise and sunset, the ever shifting panorama of the clouds, the varied colours of the forest and field and the star-sprinkled sky at night—these and many other scenes pass before our eyes on the never ending drama of light and colour which Nature presents for our benefit.

In another lecture†:

> The man of science observes what Nature offers with the eye of understanding but her beauties are not lost on him for that reason. More truly it can be said that understanding refines our vision and heightens our appreciation of what is striking and beautiful.

Clearly a different view from Goethe's who wrote that Newton's analysis of the rainbow colours "would cripple Nature's art". Among the natural phenomena that most fascinated Raman were the beautiful coronae and haloes one can see around the sun and the moon when thin clouds come in front of them. This fascination never ceased. In 1910, when he was an Assistant Accountant-General in Nagpur, his clerks noticed him at lunch-time studying the solar coronae reflected in a pool of water in front of his office. Later in Calcutta, he was seen often making observations on the lunar coronae, when taking his evening stroll in the *maidan*. I myself have seen him measuring the polarization of the coronae in 1967 in Bangalore when he was 79! Wordsworth's lines on The Rainbow come to mind:

> So was it when my life began
> So is it now that I am a man
> So will it be when I shall grow old...

Raman stated†† that purely from the size of the rings, the vividness of the colours, and the polarization characteristics, not only can one estimate the size and distribution of the particles but also deduce whether these are droplets of liquid water, amorphous solidified water or ice crystals. Raman produced these coronae in the laboratory over a wide range of droplet sizes and states that these artificial coronae are more striking in colour than those seen in Nature, as the colours of the latter were diluted by the finite angular dimensions of the sun or moon. He was often up very early in the morning at Bangalore observing the coronae formed around the planet Venus!

It is also remarkable how much science Raman could extract from his study and contemplation of this one phenomenon. I shall give three examples.

† Raman C.V., *The New Physics,* Philosophical Library Inc., New York, 1951.
* Article written to commemorate the diamond jubilee of the discovery of Raman Effect.

†† Raman C.V., *Lectures in Physical Optics,* Indian Academy of Sciences, Bangalore, 1959.

At the Niels Bohr Institute, Copenhagen

Raman's Observation of "Speckles" in 1919†

Who has not seen the *radiant spectra,* the rays that seem to emanate when a small intense source of light is viewed against a dark background — the long coloured streamers of light which are seen to diverge from the source in all directions. Raman commenced his detailed studies of this phenomenon around 1918. He noted that when the source is monochromatic, the streamers become spots and faint haloes encircle the source near the outer limit. He connected this phenomenon with the coronae.

Coronae round the sun and the moon are the result of Fraunhofer diffraction by spherical droplets. Raman argued that when radiations diffracted by the individual particles are superposed at any given point of observation, there must be interference. If the particles are distributed at random and execute rapid uncorrelated movements as in a real cloud, these interference effects will be unobservable. The observed intensity would be n times the Fraunhofer diffraction of an individual droplet (assuming n particles of equal size). If, on the other hand, the particles occupy stationary positions within the cloud, the interferences between the individual particles must be observable, even if the particles are numerous. For a random distribution of particles, while the most probable resultant intensity would be zero, the average intensity would be nA^2 (where A is the amplitude of the wave scattered by one particle). Hence a point source of monochromatic light, when viewed through a stationary cloud, will exhibit a diffraction corona on which will be "superposed" this interference effect. The net result is that instead of a continuous distribution of intensity, one would observe violent fluctuations. The corona, to use Raman's expression,must have a "mottled" appearance, each mottle being like an optical image of the original source produced by the cloud of particles! If the source is one of white light, each point is spread radially into a spectrum (the red being the farthest from the centre) giving the effect of long coloured streamers. The intensity

† Raman, C.V., *Philos. Mag.* 38, 568, 1919.

distribution of the spots will be that obtained from the random walk problem, i.e. the Rayleigh law.

Much later, Raman and his (now renowned) student GN Ramachandran verified all these deductions in coronae produced by a cloud of lycopodium particles on a glass plate. Incidentally the *mottles* of Raman are the 'speckles' which became prominent when the laser was discovered a few decades later. Raman used to project the halo produced by the colloidal particles of dilute milk and showed that the bright spots (speckles) in the central disk of the corona continually changed, appearing and disappearing in the field of view — an effect due to the Brownian motion of the colloidal particles. In 1919 Raman proposed that the diffracting structures which produced the *radiant spectra* were in the eye. They were in the refractive media of the eye — opaque or transparent particles or small regions with small differences in refractive index in the cornea, the vitreous or aqueous humour or even the lens. These ideas which he put forth anticipated, in a sense, the modern concepts of twinkling of stars and the speckle formation in telescopes — a connection which was even hinted at by him.

X-ray Diffraction by Liquids

It is almost certain that Raman's interest in crystal structure determination and in X-ray diffraction arose due to his meeting Sir William Bragg (Senior) in London. Bragg showed Raman the structure of naphthalene that he had determined. Raman's preliminary calculations showed that this structure was not consistent with the birefringence of the crystal, and the structure was later modified. This led him on to the idea of using optical and magnetic effects as accessories to X-ray methods for crystal structure determination — concepts which were so elegantly extended and perfected later by his famous student and collaborator KS Krishnan.

On his return to India he got his assistants to build an X-ray tube at the Indian Association for the Cultivation of Science. Since the theories of X-ray diffraction by a liquid were quite inadequate at that time, he (with KR Ramanathan) developed a satisfactory theory. A detailed treatment of this problem is given by AH Compton in his book *X-rays and Electrons*.

When a pencil of homogeneous X-rays passes through a thin layer of liquid and is received on a photographic plate, there appear in addition to the central spot (given by the undeviated beam) diffraction haloes surrounding the centre. The surprise is that the central disk, i.e. the first peak of the classical diffraction, is absent. Raman's interest and insight into the halo phenomenon provided the explanation. He noted that the X-ray case had to be treated differently from the optical one, since the wavelength of the radiation is of the order of the interatomic distance. The discrete structure of the medium would have to be considered when applying the Einstein–Smoluchowski fluctuation theory. These fluctuations occur over distances varying from that between molecules up to that of the containing vessel. If the density were uniform (i.e. if there are no fluctuations), no scattering would occur, as the interference would be complete. Raman showed that this theory could easily explain why liquids scattered X-rays so little at low angles. At larger angles the variations in the intermolecular distances also have to be computed to explain the spread of the halo. This was done from statistical and thermodynamical considerations again using the Einstein–Smoluchowski ideas as the basis.

The Classical Derivation of the Compton Effect

In 1924 at the British Association meeting at Toronto, Canada, there was a debate on the recently discovered Compton effect in which Compton and Raman took part. The discussion is of some interest as it underscores the problems that physics and physicists faced in 1924, just before quantum mechanics was formulated. In addition to the X-ray scattering of degraded frequency (the Compton effect), there is an unmodified secondary radiation. Compton had explained this as due to the whole group of electrons in the atom, scattering conjointly. To this view Raman raised the question:

> If one electron acting alone can scatter a quantum and also all the Z electrons in the atom acting together, then why do we not observe scattering by two, three or more electrons acting together at a time, with their corresponding fractional Compton shifts in wavelengths? To the alternative explanation of the unmodified scattering given by Professors Compton and Jauncey that it represents the scattering by an electron, which the impinging quantum is unable to detach from the atom, the equally pertinent question may be asked: then why is the intensity of this type of radiation proportional to Z^2 and not Z?

In 1927 Raman's study of the halo again came to the rescue. Using a simplified atomic model in which electrons are regarded as a gas distributed in a spherical enclosure surrounding the nucleus, he showed that the

Raman and AH Compton (*centre*)

classical wave principles led directly to a quantitative theory of the Compton effect.

> The problem is very similar to those which continually arise in such optical problems as the theory of coronae.... The answer to it can be given forth by analogy with the known results in optical cases. The resultant of the Z vibrations can be divided into two parts, *the first part* is entirely determinate, its amplitude being a function of the angle between the primary and secondary rays which is invariable with time. *The second part* is entirely indeterminate so that neither the amplitude nor the phase can be specified at any given time in any given direction and consequently the frequency is also variable. Nevertheless it is possible to specify the statistical expectation of the intensity of this second and highly *fluctuating* type of secondary radiation.

Compton and Allison, in their well-known book *X-rays in Theory and Experiments*, say:

> Raman showed from purely classical considerations that two components must exist...

and go on to give the theory of the scattering of X–rays by an electron cloud stating:

> This was probably the first time a detailed method was given for deriving the formula for the atomic scattering factor. The derivation given closely follows Raman.

It must be mentioned that Compton too derived the same results independently by a different method two years later.

This paper (which was again inspired by his interest in coronae and haloes) is an important one*.

He says in it:

> ...our expression represents merely a statistical average of a quantity that *fluctuates with time*... the fluctuations with time of the secondary radiation from the atom involve the corresponding fluctuations in the electrical state of the atom....

To avoid misapprehension it should be made clear that the fluctuations of the atom we are considering are quite different in nature from the fluctuations contemplated in thermodynamics and kinetic theory. We are here concerned with the fluctuations of the atom from its normal condition under the influence of external radiation.

It was this work which convinced him that light radiation can excite molecules and hence there must exist an optical analogue of the Compton effect — i.e. interaction between light quanta and molecular vibrations.

The Blue of the Sea

It is an open question as to how much the books one reads in one's youth influence one's activities in later years. In Raman's case, I think there appears to be a connection. I was able to trace two books which were available in Mr R Chandrasekhara Iyer's (Raman's father's) house which were *certainly* read by Raman when he was between 11 and 13.

New Fragments by John Tyndall published in 1893 contains an article "about common water" which says

> Water of the Lake (of Geneva) is known to be beautifully blue.... Blue is the natural colour of both water and ice. On the glaciers of Switzerland are found deep shafts and lakes of beautifully blue water. The most striking example of the colour of water is probably that furnished by the Blue Grotto of Capri in the bay of Naples... the walls and water of which shimmer forth a magical blue light.... The bluest of the blue waters are clear and have no detectable suspended impurities.

* Raman, C.V., *Indian J. Phys.* 3 357, 1928.

KS Krishnan

Popular Lectures on Scientific Subjects by Hermann von Helmholtz contains some magnificent essays — "On Goethe's scientific researches", "On the physical causes of harmony in music", "On the relation of optics to paintings"— essays that must have fascinated young Raman. "On ice and glaciers", Helmholtz says:

> In the depths of the crevasses, ice is seen of a purity and clearness with which nothing we are acquainted with in the plains can be compared. From its purity it shows a splendid blue colour like that of the sky, only with a greenish hue.... Their vertical dark blue walls of crystal ice glistening with moisture from the trickling water form one of the most splendid spectacles which Nature can present to us.... The beautiful blue colour they exhibit is the colour of natural water; liquid water as well as ice are blue, though to an extremely small extent, so that the colour is visible in layers from ten to twelve feet thickness.

Put these along with very different views he read, later (like the following statement by Lord Rayleigh) whose every paper Raman is believed to have read.

> We must bear in mind that absorption or the proper colour of water cannot manifest itself unless the light traverses a sufficient depth before reaching the eye. In the ocean the depth is of course adequate to develop the colour, but if the water is clear, there is often nothing to send the light back to the observer. Under these circumstances the proper colour cannot be seen. *The much admired dark blue of the deep sea has nothing to do with the colour of water, but simply the blue of the sky seen by reflection.*

Sir Asutosh Mookerjee (the Vice-Chancellor of Calcutta University) insisted that Raman should definitely go to Oxford for the Universities' Congress and this was indeed fortunate. It was on this voyage that he saw the incredible blue of the Mediterranean sea. He could not believe that the sea could be so blue and so beautiful, nor could he believe that this deep azure was "simply the blue of the sky seen by reflection". Even on board ship he disproved this conjecture of Rayleigh's noting that when the reflection of the sky by the sea is quenched with an analysing nicol prism.

> the colour far from being impoverished by suppression of the sky reflection was wonderfully improved... it was abundantly clear from the observations that the blue colour of the deep sea is a distinct phenomenon by itself....*

The rest is history; how, by applying the Einstein–Smoluchowski theory of fluctuations, he established quantitatively that the blue of the sea is due to scattering by molecules—molecular diffraction as he called it; how by laboratory experiments on ice he proved that the blue of the glaciers too arose from molecular scattering. He also showed that molecular scattering was a universal phenomenon in gases, liquids and solids, i.e. irrespective of the physical state of the scatterer.

The Scattering of Light and the Light Quanta

In 1921, even before he voyaged to England, Raman had discussed how molecular movements and molecular vibrations could affect the light scattered by a group of molecules (or a cloud of particles). He had concluded that the movements of the molecules would exhibit themselves

* Raman, C.V., *Nature (London)* 108 367, 1921.

POPULAR LECTURES

ON

SCIENTIFIC SUBJECTS

BY

HERMANN VON HELMHOLTZ

TRANSLATED BY

E. ATKINSON, Ph.D., F.C.S.

FORMERLY PROFESSOR OF EXPERIMENTAL SCIENCE, STAFF COLLEGE

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Title page of the book young Raman read

as a Doppler shift in the frequency of the incident light, that the shift would be dependent on the angle between the primary and scattered radiation and that it should vanish in the exact forward direction. From his vast experience in acoustical studies, he deduced that if the molecular vibrations are anharmonic, combination tones—sum and difference frequencies — may possibly result (E Lommel as early as 1878 considered such a possibility!). However, after his visit to England he seemed to be more concerned with understanding the mechanism of scattering. By imagining molecular scattering to take place in a black body enclosure, Raman convinced himself that Rayleigh scattering must also take place in a discontinuous manner.

> We must therefore draw the inference either that the Rayleigh law of scattering is not valid or the molecules do not scatter the radiations incident on them continuously. Since the Rayleigh law of scattering is supported by experiment, at least over a considerable range of wavelengths, it seems more reasonable to accept the latter conclusion, and to infer that the *molecular scattering of light* cannot take place in a continuous manner as contemplated by the classical electrodynamics.... We are apparently forced to consider the idea that light itself may consist of highly concentrated bundles or quanta of energy travelling through space†

This was strong support of the Einstein idea of the light quantum, a point of view not too popular at that time. As Raman said in 1922:

> Though Planck's hypothesis of quantum emission, reinforced as it has been by the success of Bohr's theory of line spectra, has passed into general acceptance, Einstein's idea of light-quanta has apparently been regarded as unnecessarily revolutionary in character.

In 1922, Einstein was awarded the Nobel Prize for his services to theoretical physics and for his work on the photoelectric effect. Pais, in Einstein's biography, says,

> Even when the Einstein photoelectric law was accepted, almost no one but Einstein himself would have anything to do with light quanta!

About two years before his death, Nagendra Nath, another of Raman's reputed students, told me that in the thirties, Max Born had told him that he was impressed with Raman's strong advocacy of Einstein's concept of the light quantum in 1921, that he was very pleasantly surprised at Raman's grasping the basic theoretical implications of the Kramers – Heisenberg process, but was truly astounded by Raman's insight in 1922 that Maxwell's field equations would have to be modified to suit the quantum theory!

In the last chapter of his monograph *Molecular Diffraction of Light* Raman writes:

> The belief in the validity of Newtonian dynamics as applied to the ultimate particles of matter has, however, received a rude shock from the success of the quantum theory as applied to the theory of specific heats, and there seems no particular reason why we should necessarily cling to Newtonian dynamics, in constructing the mathematical framework of field-equations which form the kernel

† Raman, C.V., *Molecular Diffraction of Light,* Calcutta University Press, 1922.

Raman and Heisenberg (*right*)

of Maxwell's theory. Rather, to be consistent, it is necessary that the field-equations should be modified so as to introduce the concept of the quantum of action. In other words, the electrical and magnetic circuits should be conceived not as continuously distributed in the field but as discrete units each representing a quantum of action, and possessing an independent existence.

These words were written in 1922. It is interesting that this programme suggested here of quantizing the electromagnetic field was commenced by Dirac in 1928 and by Heisenberg in 1930!

The Discovery of the Raman effect

After the publication of this monograph in February 1922, the search started.

> Bohr's theory has made the idea familiar that the emission or absorption of light from the atom or the expulsion of an electron involves something in the nature of a catastrophic change. If, therefore, we wish to look for experimental support for Einstein's conception that light itself consists of quantum units, we must consider those optical phenomena in which obviously no such catastrophic change in the atoms or molecules is involved. The molecular diffraction or scattering of light is obviously such a phenomenon.

Even from the beginning, Raman's intuition seems to have told him to look for a change in colour in scattering. He and his collaborators used sunlight and the method of complementary filters to detect this change. Strangely enough, even in the earliest of these experiments he did with KR Ramanathan, this colour change was noticed, but it was attributed to "a weak fluorescence" caused by impurities. At the insistence of Raman, the liquid was purified again and again but the effect persisted. Said Ramanathan to me later:

> Even in 1923, Prof. Raman refused to believe that this "weak fluorescence" was due to impurities. He said time and again that he felt it was a genuine effect.

The "weak fluorescence" also showed polarization effects but Raman did not, for some strange reason, follow up this important clue as he did later in 1928. In 1924, the "weak fluorescence" was again observed by KS Krishnan and in 1925, Raman asked S Venkateswaran to try to obtain a spectrum of this "weak fluorescence" but no spectrum could be recorded. I have not been able to determine whether this attempt had anything to do with the appearance of the Kramers – Heisenberg paper earlier the same year.

Things came to a head in the fall of 1927. Raman, on a holiday in Waltair, worked on and wrote the paper on the classical derivation of the Compton effect and came back to Calcutta convinced that an *optical analogue of the Compton effect* must exist; and S Venkateswaran, one of the most diligent of Raman's collaborators, made the remarkable observation that the so-called "fluorescence" in glycerine was strongly polarized. This clearly indicated to Raman that the phenomenon could not be the conventional fluorescence — a point of view he had always taken and for which he was seeking proof.

Venkateswaran was a part-time student who could only work after working hours and on holidays. Raman wanted someone to use the sunlight available all through the day, particularly as he himself had lecturing commitments at the university. And so he persuaded

Raman examining flowers

KS Krishnan, the best student he had at that time, to get on to these experiments. Krishnan's diary says

> 5th February 1928: for the past three or four days, I have been doing some experimental work... the last experimental work I did was in the summer of 1926....
>
> As Professor says it is not quite healthy for a scientific man to be out of touch with actual experimental facts for any length of time.

Krishnan takes up the problem assigned to him as a dutiful Indian student would, but he is obviously not convinced of the reasons for pursuing these experiments. But within a few days this line of attack led to momentous discoveries.

> ... I took up (at the suggestion of Prof.) the general problem of the 'fluorescence' of organic vapours, rather than the pressing nature of any specific problem in the subject, awaiting experimental solution which usually draws a man to a new field ...studied anthracene vapour. It exhibits strong 'fluorescence'; which does not show any polarization....

Raman tactfully suggests changing over first to the study of organic liquids, particularly to that of the polarization of the scattered light, and verifying his earlier observations.

> Professor has been working with me all the time. Recently, Professor has been studying with Mr Venkateswaran the fluorescence exhibited by many aromatic liquids.... However, in view of the fact that anthracene vapour does not show any polarization, Professor has asked me to verify again his observations on the polarization in some of the liquids....

It is remarkable that within two days of Raman's suggestion, Krishnan confirms the observations of Raman and Venkateswaran in many liquids.

> Tuesday, 7th February ... all pure liquids show fairly intense 'fluorescence' ... and what is much more interesting, all of them are strongly polarized.

Raman verified these observations and wonders why he missed discovering this phenomenon as early as 1923 when Ramanathan had made similar observations.

> He was very much excited and repeated several times that it was an amazing result.... One after the other, the whole series of liquids were examined and everyone of them showed the phenomenon without exception. He wondered how we missed discovering all that five years ago.

Raman then realises that this was the effect he had been looking for since 1922 (or 1925), a scattering with a modified frequency due to the Kramers–Heisenberg process.

> ...Professor suddenly came to the house (at about 9 p.m) and called for me. When we went down, we found he was very much excited and had come to tell me that what we had observed this morning must be the Kramers–Heisenberg effect we had been looking for all these days. We therefore agreed to call the effect *modified scattering*.... He repeatedly emphasized the exciting nature of the discovery.

Raman then asks Krishnan to go back to the study of vapours to investigate the "modified scattering" in them.

> Thursday, 9th February.... Tried ether vapour and it was surprising that the modified radiation was conspicuous.... Professor came from the college at about three... and there was enough sunlight to see for himself

and Raman was in a state of euphoria—a man who had at last come to the end of a trail.

He ran about the place shouting all the time that it was a first rate discovery, that he was feeling miserable during the lecture because he had to leave the experiment.... He asked me to call everybody in the place to see the Effect and immediately arranged, in a most dramatic manner, with the mechanics to make arrangements for examining the vapours at high temperatures.

All that remains is to observe it and record it in a spectrograph.

Tuesday 28th February: On examining the track with a direct vision spectroscope, we found to our great surprise, the modified scattering was separated from the scattering corresponding to the incident light by a dark region.... This encouraged us to use monochromatic incident light.

I close my article with some remarks S Chandrasekhar the astrophysicist of Chicago made recently.

I have an equally vivid recollection of a day in early March in 1928, when Professor Raman visited our home in Madras on his way to Bangalore where on the 16th of March he was to give the address announcing his discovery of what was soon called the Raman effect. I remember well his showing slides of the first Raman spectra ever taken and of the state of euphoria he was in. On that occasion someone drew attention to the discovery of the Compton effect a few years earlier, and Raman responded with 'Ah, but my effect will play a great role for chemistry and molecular structure!' That statement was indeed prophetic. Later, during the summer of 1928, I spent two months at the Indian Association for the Cultivation of Science at Raman's laboratory where at that time there were many young men who together with Raman were pursuing the new discovery. Among them were several who were later to become leaders of Indian science.... You can imagine what a marvellous experience it must have been for a young man* to have witnessed at such close quarters a group of enthusiastic scientists caught in the wake of a great discovery.

* Chandrasekhar was only 17 then

Raman and S Chandrasekhar.
Lalitha Chandrasekhar is partly seen.

THE PICTURES

The Early Days

People and places

The pond in his ancestral village Purasakkudi

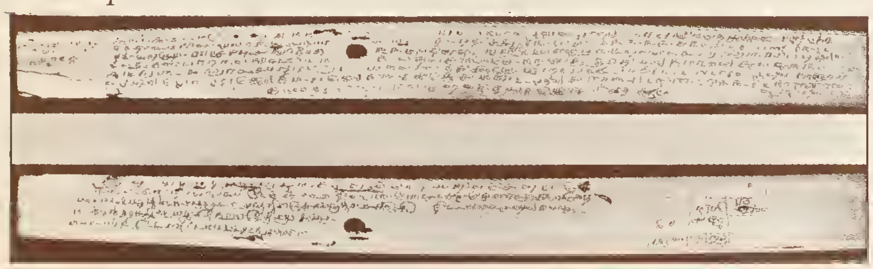
A lane in ancestral village

Ancestral House of Raman's family — Purasakkudi

House in Thiruvanaikkaval where Raman was born.

Room in which Raman was born. ►

Raman's Horoscope in Tamil-1888. Raman had no belief in horoscope.



Tiruchirapalli - Rockfort Temple and tank.

R. Chandrasekhar Iyer (Father)

Parvathi Ammal (Mother)

Gnanambal (Raman's Aunt)

Brothers and Sisters

Subramanyan (1886 – 1959)

Mangalam (1891 – 1914)

C Ramaswamy (1907 –

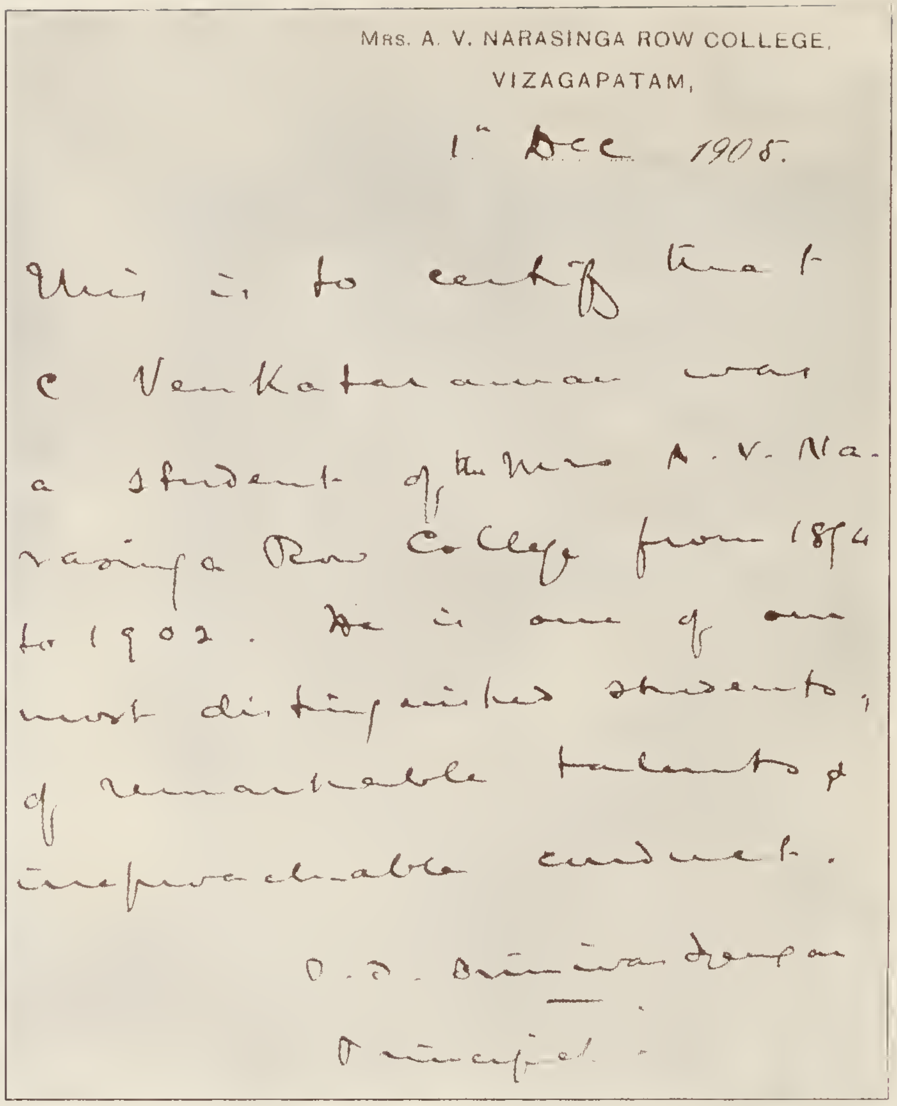
Venkataraman (1888 – 1970)

Kumaraswamy (1894 – 1914)

Meenakshi (1903 – 1912)

Sundaram (1898 – 1907)

Sitalaxmi (1901 – 1971)


MRS. A. V. NARASINGA ROW COLLEGE,
VIZAGAPATAM,

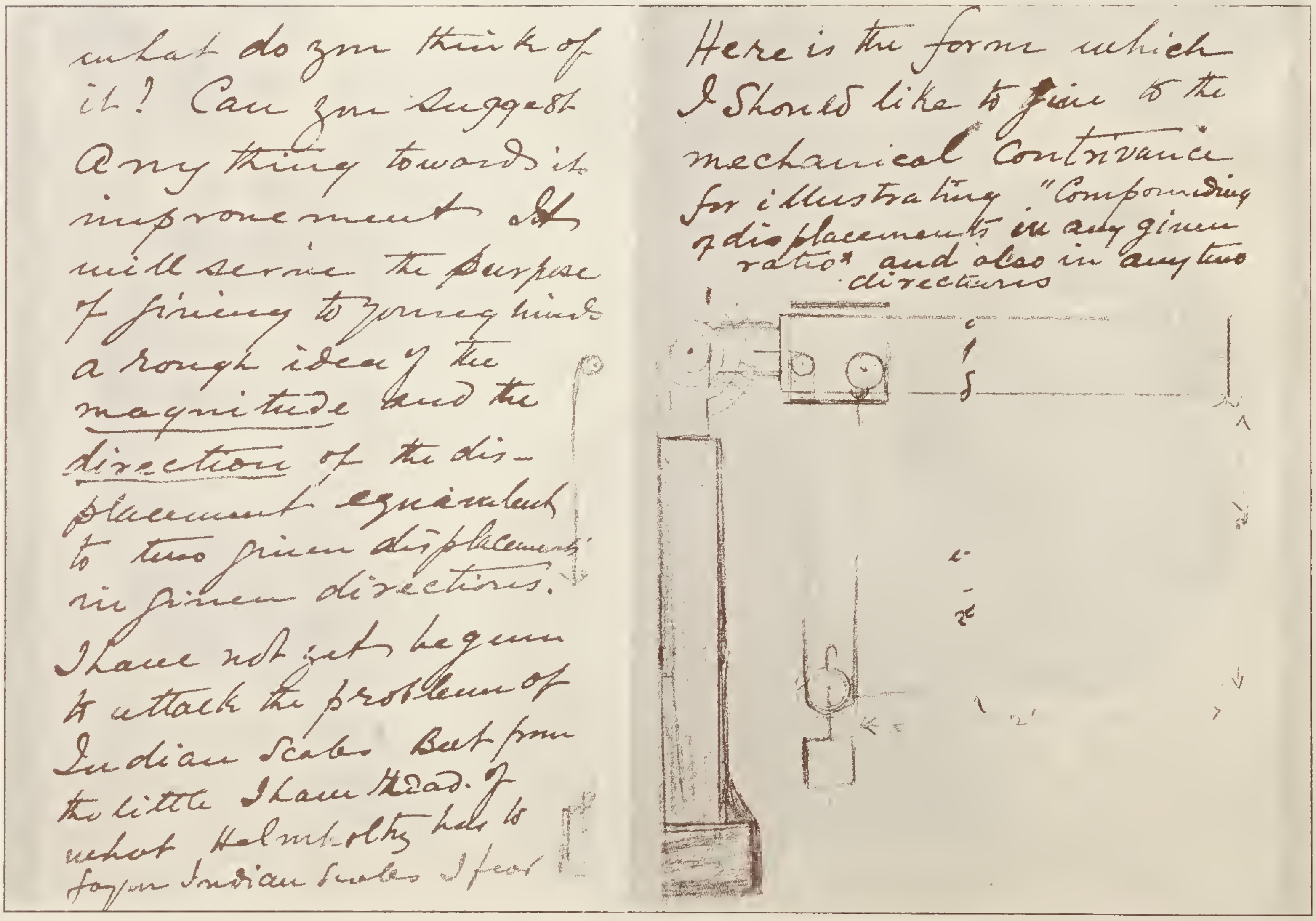
1st Dec 1905.

This is to certify that C Venkataraman was a student of the Mrs A. V. Narasinga Row College from 1874 to 1902. He is one of our most distinguished students, of remarkable talents & irreproachable conduct.

P. T. Srinivasa Iyengar
Principal.

Certificate from Principal Mrs. A.V.N. College

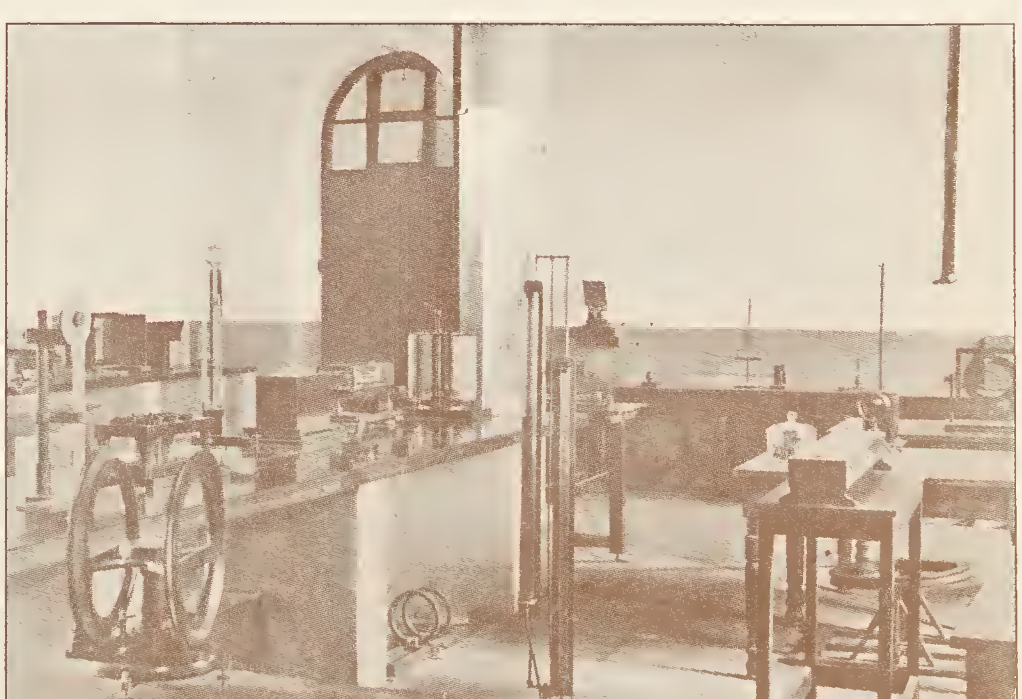
Letter to young Raman from his father consulting him on the teaching of mechanics to his students.


what do you think of it? Can you suggest anything towards its improvement. It will serve the purpose of giving to young minds a rough idea of the magnitude and the direction of the displacement equivalent to two given displacements in given directions. I have not yet begun to attack the problem of Indian Scales. But from the little I have read of what Helmholtz has to say on Indian Scales I fear

Here is the form which I should like to give to the mechanical contrivance for illustrating "Compounding of displacements in any given ratio" and also in any two directions

Raman in Madras

The Presidency College



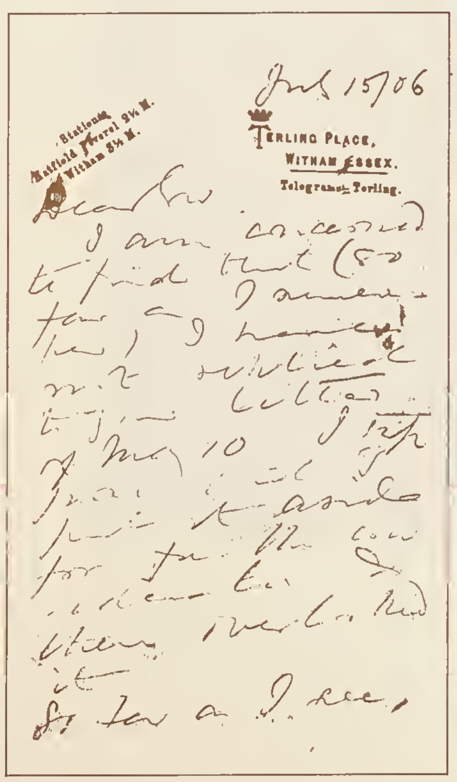
The Physics Laboratory, Presidency College

Madras Marina Beach

The English classes were conducted by Professors Bilderbeck and Elliot. They held their classes usually in the big lecture hall overlooking the sea, and the seats were then so arranged that if the students did not like the lecture, they could instead gaze at the far horizon of the blue sea or count the glittering waves as they crashed down on the beach. Did ever students of the English language have a more marvellous panorama, the contemplation of the beauty of which could lighten their labours? I am almost tempted to compare it with that glorious theatre built by the ancient Greeks on the heights of Taormina, from which you could see the waves of the Ionian sea washing the coast of Sicily, or turning your eyes up, you could see the glittering snows on Mount Etna! It must be said to the credit of the teachers I have mentioned that they often did hold our attention in spite of the lure of the swirling waters of the ocean breaking upon the shore. Or was it because of the same fascinating vision of the sea that our minds were better attuned to the complicated beauties of the English language? I have vivid memories of the spirit with which Professor J. B. Bilderbeck conducted his classes and sought to infuse into us a due appreciation of the great English writers.

Presidency College – Group photograph

Letter from Lord Rayleigh to Raman (1906)



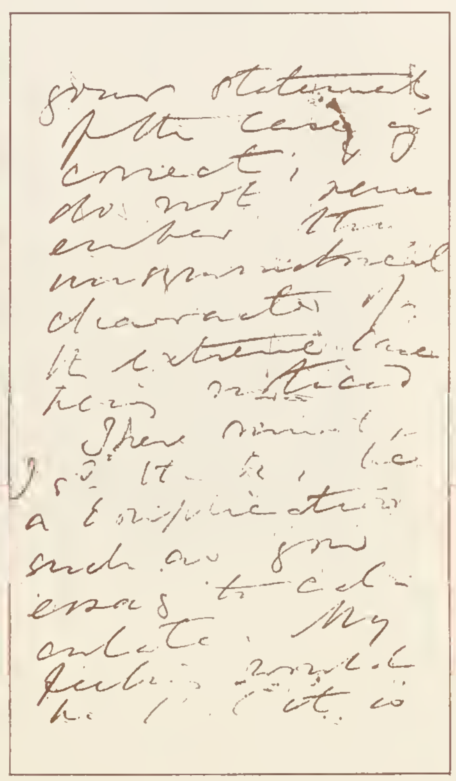
July 15/06

Terling Place,
Witham Essex.
Telegrams: Terling.

Stations: Hatfield Peverel 3½ M. Witham 3½ M.

Dear Sir,

I am concerned to find that (so far as I remember) I have not noticed your letter of May 10. [illegible] So far as I see,



your statement of the case is correct; I do not remember the nonsymmetrical character of the extreme lines being noticed.

There would, I suppose, be [illegible] a [illegible] such as you essay to elaborate. My feeling would be [illegible]

Raman in 1906 as college student

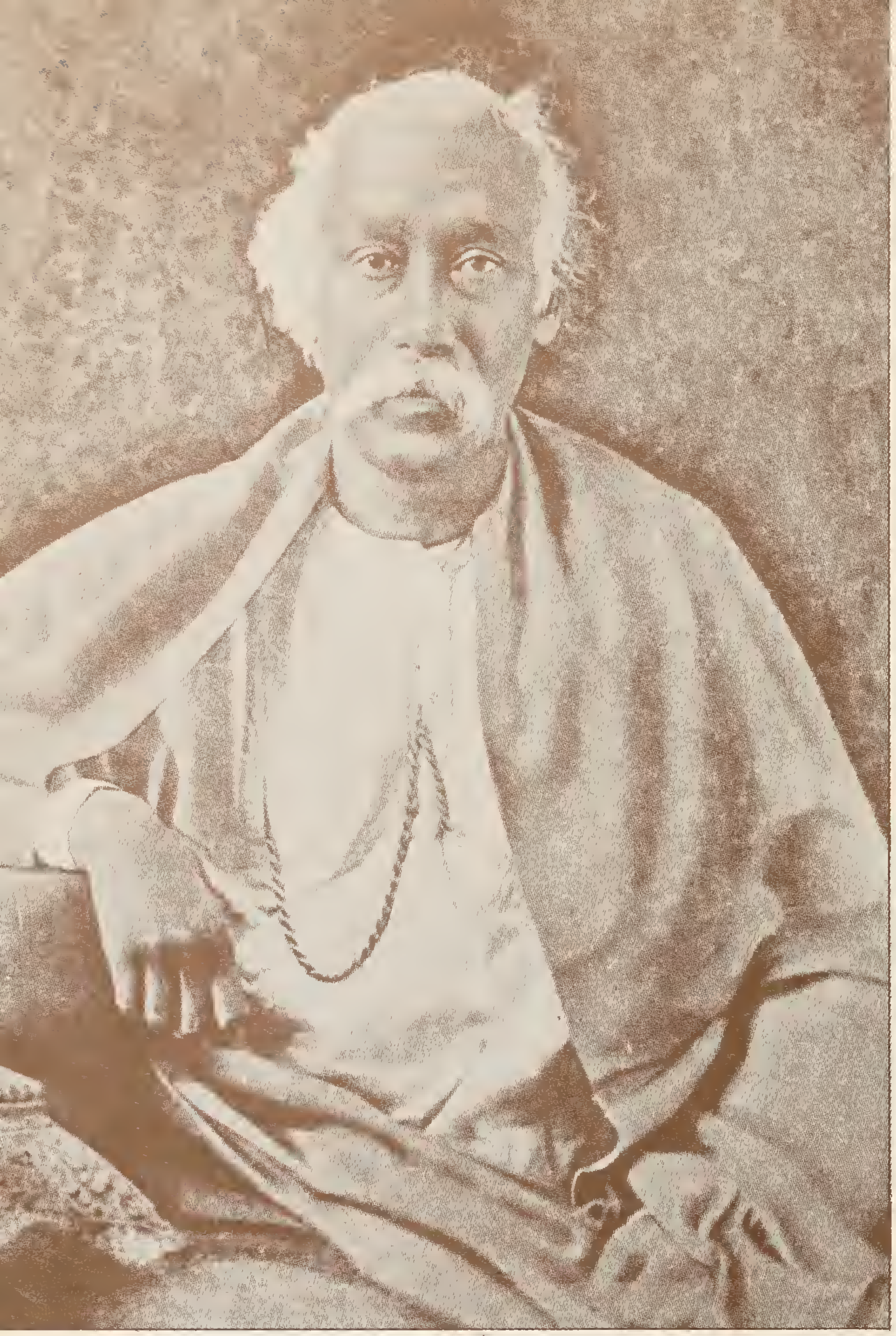
Raman in 1907 as Assistant Accountant General

Lokasundari

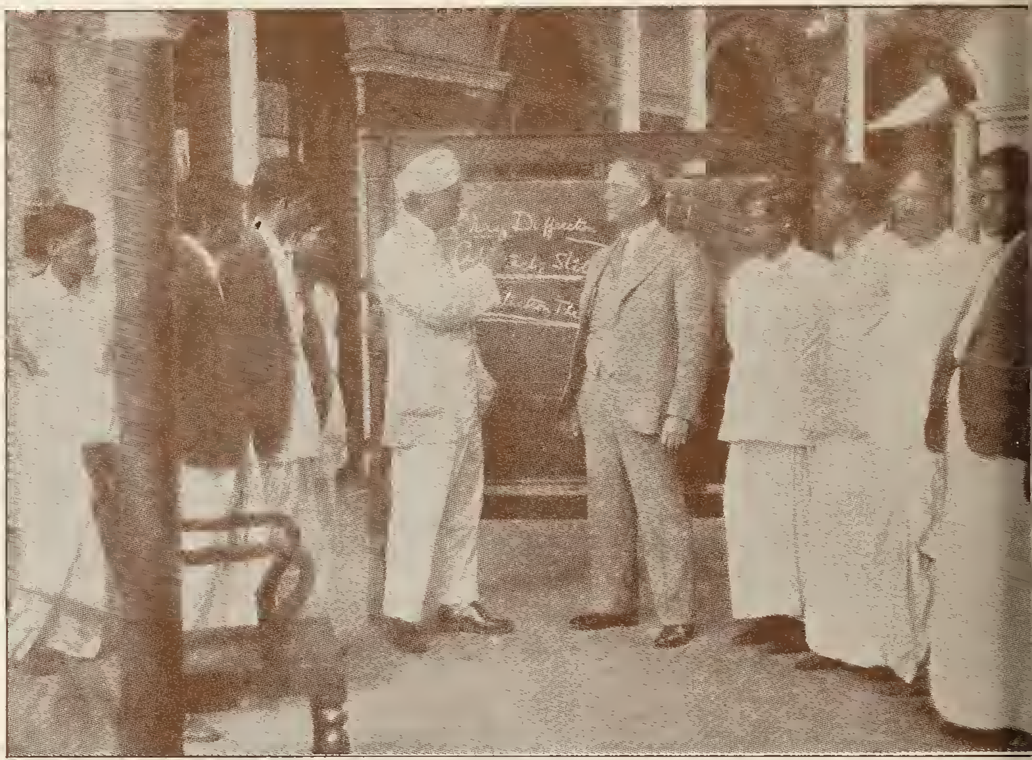
Group photograph – Accountant General Office, Rangoon

Raman in Calcutta

The Esplanade



Mahendra Lal Sircar

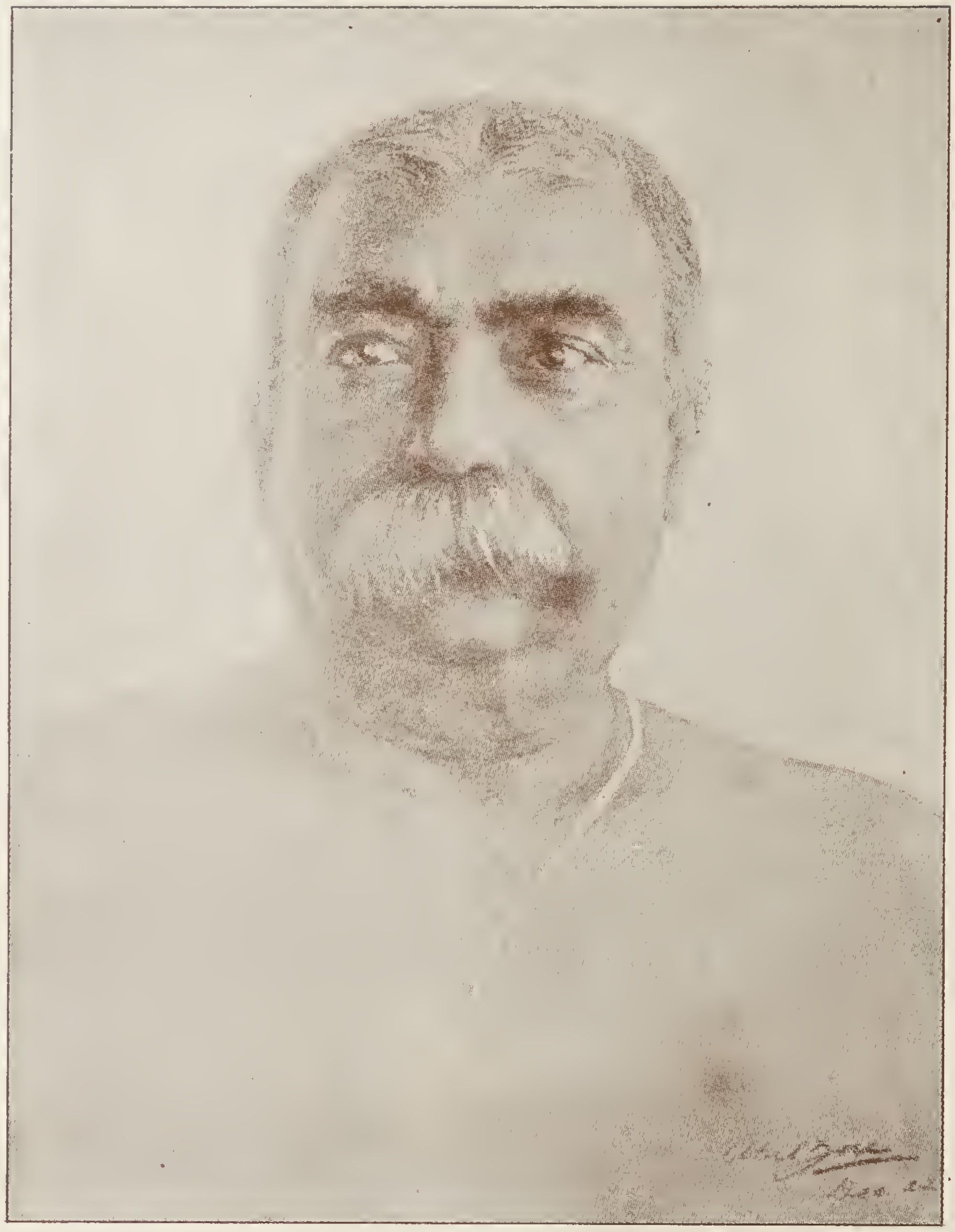


Seminar at the Indian Association

The Indian Association for the Cultivation of Science

Church in Scots Lane

Gharries in the monsoon



Asutosh Mookerji

Sommerfeld at Science College

Science College, Calcutta

No. 6748

From

P. BRÜHL, Esq., D.Sc., I.S.O., F.C.S., F.G.S.,

Registrar, Calcutta University,

To

C. V. Raman, Esq., M.A.

Senate House, the 26 · 3 · 1914

Sir,

With reference to your letter of the 14th current I am directed to inform you that the Hon'ble the Vice-Chancellor and Syndicate agree to the condition on which you are prepared to accept the appointment of Sir Taraknath Palit, Professor of Physice, namely, that during your incumbency you will not be required to leave India and to proceed to any foreign country.

I have the honour to be,

Sir,

Your most obdt: servant,

P. Brühl

Registrar.

Letter from Registrar

the Governing Body, grant leave on conditions analogous to those prescribed in the Civil Service Regulations for officers in the Indian Educational Service.

III. That the Sir Taraknath Palit Professorship of Chemistry be offered to Dr. Prafullachandra Ray, C.I.E., Ph.D. (Cal.), D.Sc. (Edin. & Durham), F.C.S., Professor of Chemistry in the Presidency College, Calcutta.

Dr. Ray has established his reputation as an investigator by his researches in the exact constitution of the Nitrites and all Oxy-nitrogen compounds of Mercury and other allied bodies, published in numerous papers in the Journal of the Chemical Society of London, the Proceedings of the Royal Society of Edinburgh, the Zeitschrift fur Anorganische Chemie, Liebig's Annalen, the Journal of the Asiatic Society of Bengal and other scientific periodicals. Dr. Ray is also the author of a standard work on the History of Hindu Chemistry. In recognition of his work as an investigator, the University conferred upon him the Honorary Degree of Doctor of Philosophy on the occasion of the Jubilee Celebrations in 1908.

IV. That the Sir Taraknath Palit Professorship of Physics be offered to Mr. C. V. Raman, M.A.

Mr. C. V. Raman had a brilliant academic career in the University of Madras and is now an officer in the Indian Finance Department. His first paper on "Unsymmetrical Diffraction Bands due to a Rectangular Aperture" was published in the Philosophical Magazine in 1906, while he was still an M.A. student. Since then, he has been steadily engaged in research work, which has latterly been carried on principally in the Laboratory of the Indian Association for the Cultivation of Science. His investigations on the theory of Vibrations and on Optics, which have attracted considerable notice among European Physicists, are embodied in twenty-two papers, of which seven have been published in the Philosophical Magazine, three in the Physical Review, six in Nature and the remainder in the Journal of the Indian Mathematical Society and the Bulletin of the Indian Association for the Cultivation of Science. In 1913, the University of Madras awarded to Mr. Raman the Maharaja of Trivandrum Curzon Prize for Research.

(Confirmed.)

ASUTOSH MOOKERJEE, *Vice-Chancellor.*

P. BRÜHL, *Offg. Registrar.*

C. U. Press—Reg. No. 604—26-1-14—300.

Office order of appointment to Palit Professorship

Group photograph — Calcutta University

Raman and Lokasundari

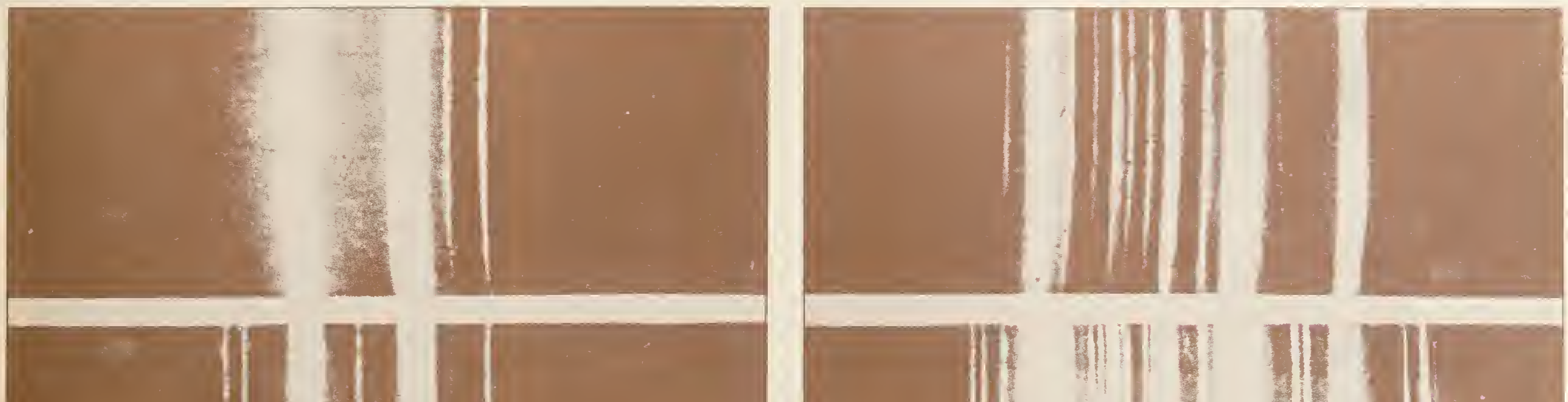
Group photograph — Science Congress

The Raman Effect

Discovery and the Nobel Ceremony

Raman with spectrograph and Raman tube

First Raman spectra photographed



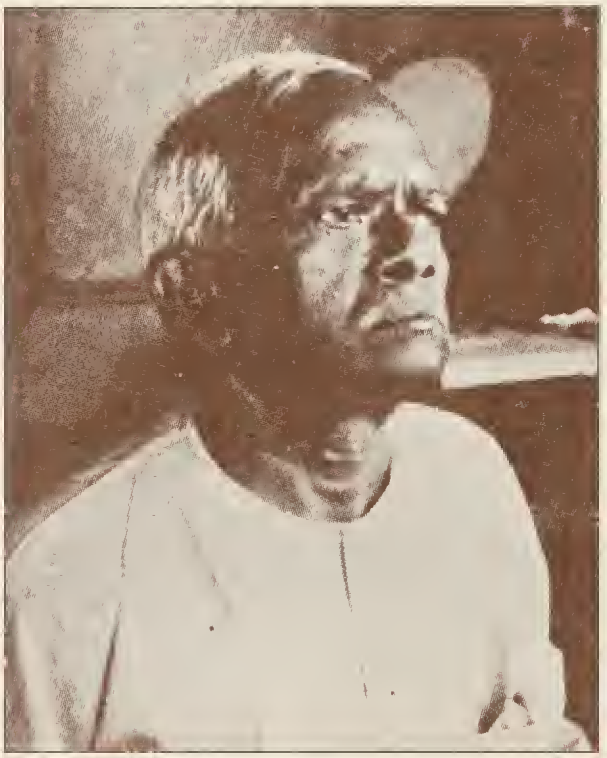
Students of Raman

KR Ramanathan

KS Krishnan

S Venkateswaran

Seshagiri Rao



Ashutosh Dey

S Ramachandra Rao

D Ramakrishna Rao

Kameswara Rau

AS Ganeshan

NEW THEORY OF RADIATION

PROF. RAMAN'S DISCOVERY

(ASSOCIATED PRESS OF INDIA.)

CALCUTTA, Feb. 29.

Prof. C. V. Raman, F. R. S., of the Calcutta University, has made a discovery which promises to be of fundamental significance to physics. It will be remembered that Prof. A. H. Compton of the Chicago University was recently awarded the Nobel Prize for his discovery of the remarkable transformation which X-rays undergo when they are scattered by atoms. Shortly after the publication of Prof. Compton's discovery, other experimenters sought to find out whether a similiar transformation occurs also when ordinary light is scattered by matter and reported definitely negative results. Prof. Raman with his research associates took up this question afresh, and his experiments have disclosed a new kind of radiation from atoms excited by light.

The new phenomenon exhibits features even more startling than those discovered by Prof. Compton with X-rays. The principal feature observed is that when matter is excited by light of one colour, the atoms contained in it emit light of two colours, one of which is different from the exciting colour and is lower down the spectrum. The astonishing thing is that the altered colour is ~~quite~~ independent of the nature of the substance used. It changes however with the colour of the exciting radiation, and if the latter gives a sharp line in the spectrum, the second colour also appears as a second sharp line. There is in addition a diffuse radiation spread over a considerable range of the spectrum. He will deliver a lecture demonstrating these phenomena first at Bangalore on the 16th March.

First newspaper announcement of the Discovery of the Raman Effect made on 28th Feb. 1928

SOUTH INDIAN SCEINCE ASSOCIATION, BANGALORE.

EIGHTH ANNUAL SESSION.

FRIDAY - 16th March 1928: -

6 P.M. Welcome Address by the President of the Association.

6-15 P.M. Inaugural Address by Prof.C.V.Raman,F.R.S.,

SUBJECT: -

"A new Radiation".

Notice of the historic lecture in Bangalore where the Raman effect was announced (16th March 1928)

24

A New Radiation[1]

BY

PROF. C. V. RAMAN, F.R.S.

(Plate XII).

1. *Introduction.*

I propose this evening to speak to you on a new kind of radiation or light-emission from atoms and molecules. To make the significance of the discovery clear, I propose to place before you the history of the investigations made at Calcutta which led up to it. Before doing so, however, a few preliminary remarks regarding radiation from atoms and molecules will not be out of place.

Various ways are known to the physicist by which atoms or molecules may be caused to emit light, as for instance, heating a substance or bombarding it with a stream of electrons. The light thus emitted is usually characteristic of the atoms or molecules and is referred to as *primary* radiation. It is also possible to induce radiation from atoms and molecules by illuminating them strongly. Such light-emission is referred to as *secondary* radiation. The familiar diffusion of light by rough surfaces may be cited as an example of secondary radiation, but strictly speaking, it hardly deserves the name, being an effect occuring at the boundaries between media of different refractive indices and not a true volume-effect in which all the atoms and molecules of the substance

[1] Inaugural Address delivered to the South Indian Science Association on Friday, the 16th March, 1928, at Bangalore.

First page of lecture-published on 31st March 1928 in the Indian Journal of Physics

Venkateswaran

~~At night~~ After meals at night ~~[illegible]~~ and myself were chatting together in our room when Prof. Raman came to the (about 9 P.M.) house and called for me ~~[illegible]~~ 9 p.m. When we went down we found he was very much excited and had come to tell me that what we had observed this morning must be the ~~Kramers~~ Heisenberg effect we had been looking for all these days. We finally agreed to call the effect modified scattering rather than [illegible] We were talking in front of the house for ~~[illegible]~~ more than a quarter of an hour when he repeatedly emphasised the ~~[illegible]~~ exciting nature of the discovery,

Extract from K S Krishnan's diary

Raman receiving the Nobel Prize from the King of Sweden

C V Raman and the other Nobel Prize winners of 1930 (Hans Fischer, Karl Landsteiner and Sinclair Lewis)

Nobel Ceremony – Raman first row extreme left sitting under the British Flag

Raman and Lokasundari in Stockholm

Lokasundari and Princess Ingrid of Sweden

both evoked universal expressions of interest and pleasure. The brief addresses made by Dr. Landsteiner and Mr. Lewis at the banquet, which was given in honor of the Nobel prize winners at the Town Hall on the evening following the prize-giving ceremony, were both simple in expression but adequate.

In this connection it may be interesting to remark that of the prize winners the day was easily carried however by Sir Venkata Raman, the Indian prize winner, who, upon returning to his seat on the platform after receiving his prize from the hand of the King, was visibly moved by his emotion and sat with the tears streaming down his face. At the banquet that evening his speech was a masterpiece of eloquence, which called forth tremendous applause from a banquet-weary gathering not noted for their responsiveness. Less appreciative was, perhaps, the British Minister, who sat one place removed from me, who was forced to listen with equanimity to Sir Venkata Raman's reference - brief though it was and in passing only - to the congratulatory telegram which he had received "from his dearest friend who was now in jail".

Very respectfully yours,

LR
3-8-1957

Edward Savage Crocker
Edward Savage Crocker
Chargé d'Affaires ad interim

In quintuplicate.
File No. 090.

With Other Greats

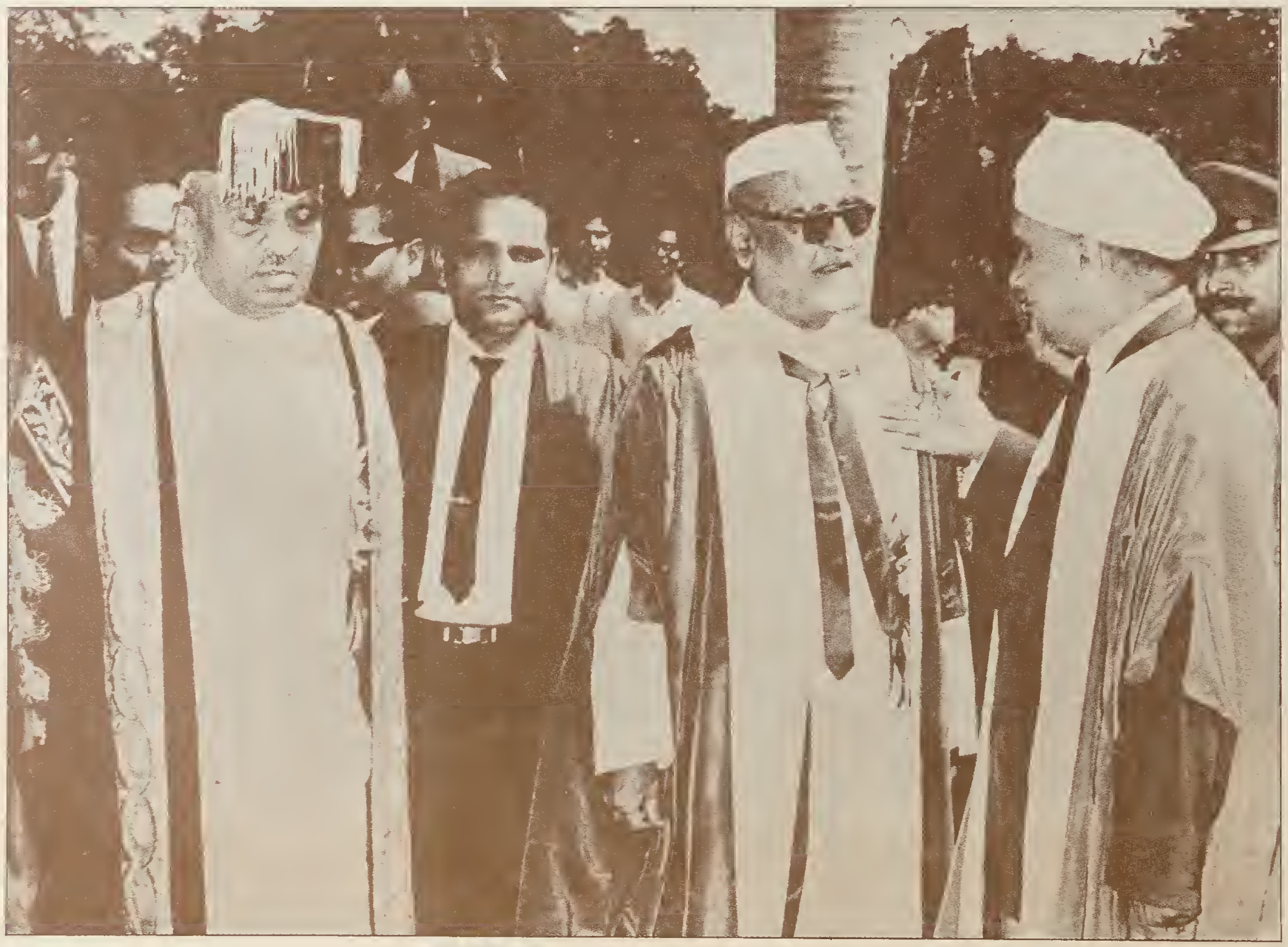
With Mahatma Gandhi and Mahadeo Desai

Lokasundari with Kasturba Gandhi

With Jawaharlal Nehru

C V Raman with Rajendra Prasad

C V Raman with Zakir Hussain



With Heisenberg

With Dirac

Raman with other Nobel Prizemen at the Lindau Conference

Raman showing diamonds to Bernal

With Pauli

With Yukawa

Inauguration of Indian Academy of Sciences Sir Mirza Ismail and Prof Max Born on either side of CV Raman

▼ *K S Krishnan, S S Bhatnagar, Sydney Chapman and C V Raman*

Sir T Vijayaraghavachariar, Arcot Ramaswami Mudaliar & C V Raman

CV Raman with delegates of IASc

At Hyderabad-Raman talking to S Bhagavantam [68]

Sir J C Ghosh and Sir C V Raman [67]

Birbal Sahni and Radhakrishnan on either side of Raman

Alladi Krishnaswamy Iyer (extreme left) Sir PS Sivaswami Ayyer (fourth from left) and others with Raman

With Mr P E Subrahmania Iyer

Rutherford

Mme. Curie

Max Born

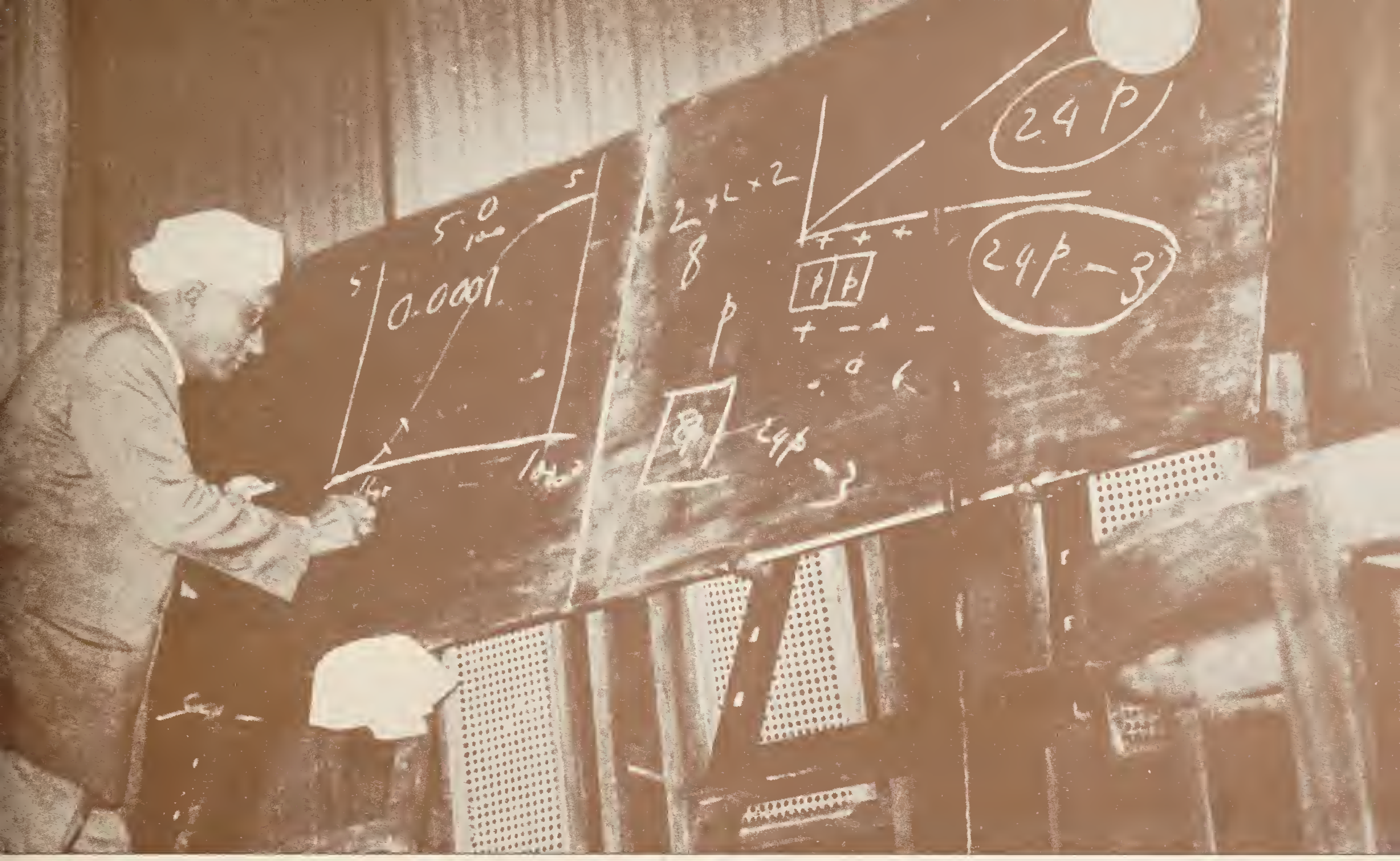
R. A. Millikan

◄ *Hedi Born*

Raman in the Lab

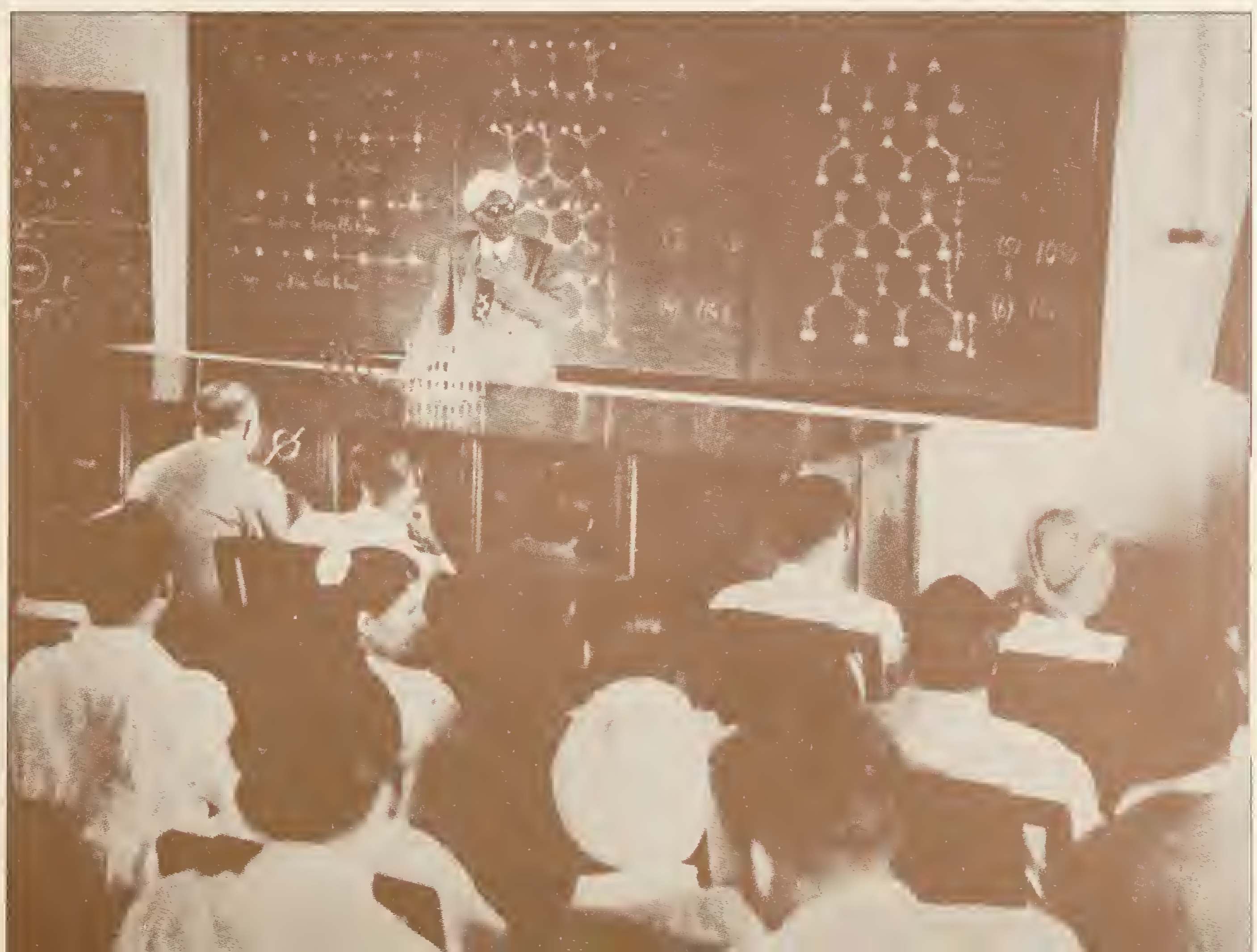
Raman and His Lectures

— in Classrooms and Crowded Halls



Raman expounding his crystal dynamics

Gandhi Memorial Lecture



Lectures in Europe

◀ *Raman giving seminar*

Seminar at Brooklyn USA ▶

◀ *Raman with Scientists*

Talk in Europe ▶

opular lectures in ▶
ndia in Pandal

Raman and Institutions

The Indian Institute of Science

J N Tata Statue

Group photograph — IISc Bhabha, Neher, Millikan, Pickering, Raman and Ramanathan

Cavendish Laboratory,
Cambridge.

3rd August 1937.

My dear Raman,

I have just received your letter on my return from a few days' holiday in the country.

I am pleased to hear that you will be able to continue your work in Physics in Bangalore without all the worries and distractions involved in acting as Director of the Institute. Now that the matter is settled, I trust that you will be able to carry on with your personal work and let bygones be bygones. It seems to me highly important that the staff at Bangalore should all pull together for the good of the Institute.

I note that the tour arranged in India includes Madras and Bangalore on our return journey. I am not yet quite sure of my plans, but it may be that I shall have the opportunity of meeting you on my travels.

Yours very sincerely,

Rutherford

Letter from Lord Rutherford

Sri Prakasha and Raman at the Raman Research Institute — Mineral Museum

Visitors at the Raman Research Institute Museum

Raman Research Institute — early stages of construction, 1948 – 1949

Raman Research Institute — early stages of construction, 1948 – 1949

Visitors at the Raman Research Institute

Student visitors at the Raman Research Institute

Raman and Children

Raman – Portrait Gallery

Moods and Styles

Portrait Gallery





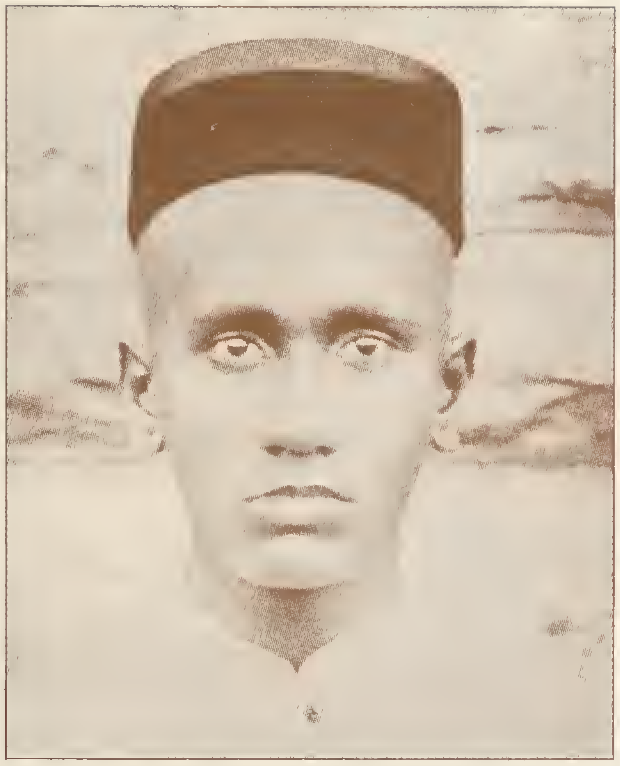







Hair Styles

Dress Styles



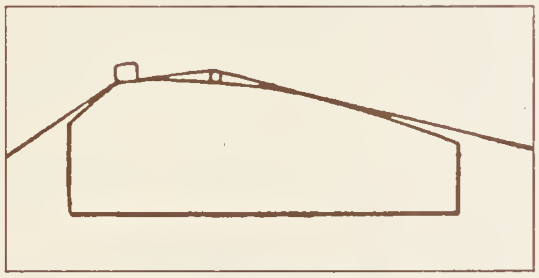
On Sound and Light

THE ACOUSTICAL KNOWLEDGE OF THE ANCIENT HINDUS.

C. V. RAMAN, M.A.,
Sir Taraknath Palit Professor of Physics, University of Calcutta.

1. Introduction.

Music, both vocal and instrumental, undoubtedly played an important part in the cultural life of ancient India. Sanskrit literature, both secular and religious, makes numerous references to instruments of various kinds, and it is, I believe, generally held by archaeologists that some of the earliest mentions of such instruments to be found anywhere are those contained in the ancient Sanskrit works. Certain it is that at a very early period in the history of the country, the Hindus were acquainted with the use of stringed instruments excited by plucking or bowing, with the transverse form of flute, with wind and reed instruments of different types and with percussion instruments. It is by no means improbable that India played an important part in the progressive evolution and improvement of these instruments and might have served as a source from which their knowledge spread both eastwards and westwards. It would form a fascinating chapter of history to try and trace the gradual development of musical instruments and musical knowledge, from the rhythmic chanting of the Rgveda in the ancient home of the Aryan race to the Indian music of the present day. But the materials available for the writing of this history seem to be all too meagre. Much of the long period over which the gradual evolution must have spread lies in the dim and remote past of which but the vaguest glimpses can be obtained from such records as exist. Something more definite regarding the acoustical developments in Ancient India might perhaps be gleaned from a study of the musical instruments, the models of which have been handed down as heirlooms for untold generations. Several of the Indian stringed instruments, for example, disclose in their design, even on a superficial examination, a quite remarkable appreciation of the principles of sound-production and of resonance. A fuller study



BULLETIN No. 15.

The Indian Association for the Cultivation of Science.

Contents:

On the Mechanical Theory of the Vibrations of Bowed Strings and of Musical Instruments of the Violin Family, with Experimental Verification of the Results: Part I.

By C. V. Raman, M.A., Life-Member and Vice-President, Indian Association for the Cultivation of Science.

CALCUTTA:
Printed at the Baptist Mission Press and Published by the Indian Association for the Cultivation of Science, 210, Bow Bazar Street, Calcutta.

1918.

Price, Rs. 2/8 : or 3s. 4d.

XV. On Whispering Galleries.

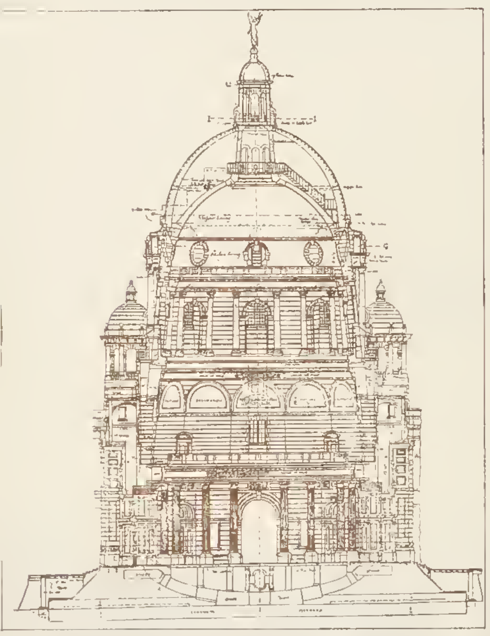
By C. V. Raman, M.A., Hon. D.Sc., Palit Professor of Physics in the Calcutta University.

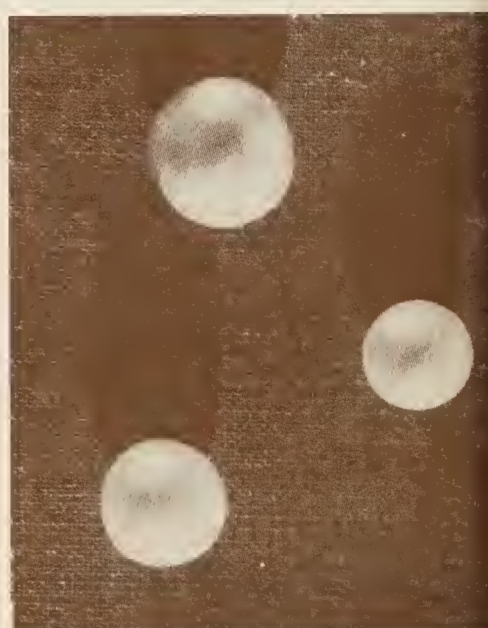
(Plates X, XI, XII, XIII and XIV.)

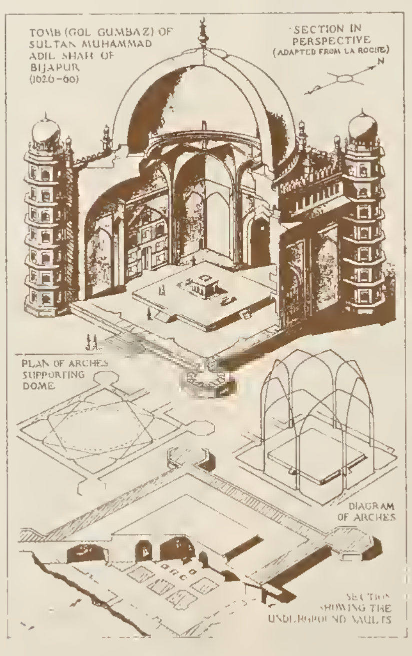
CONTENTS.

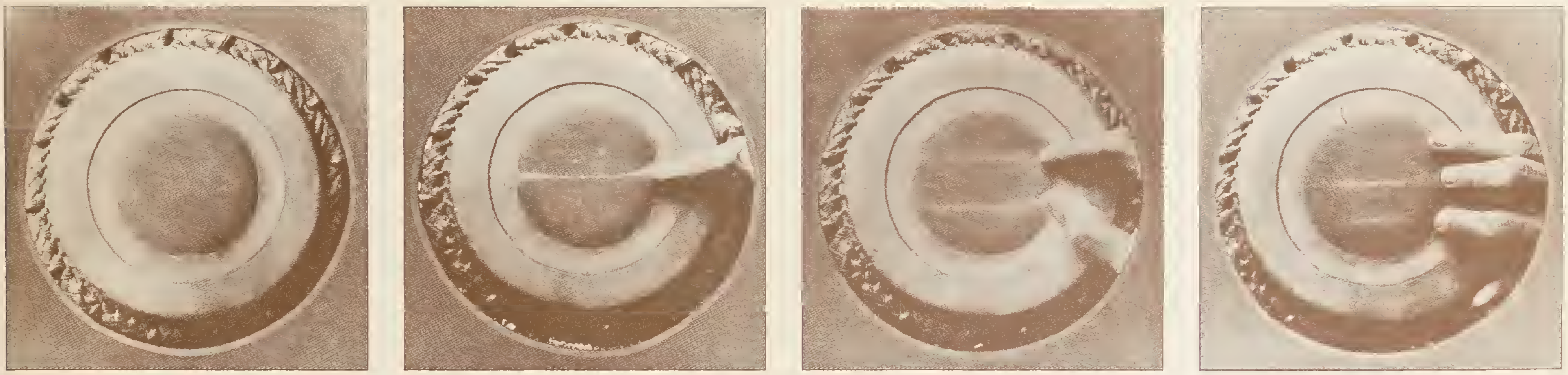
I.—Introduction.

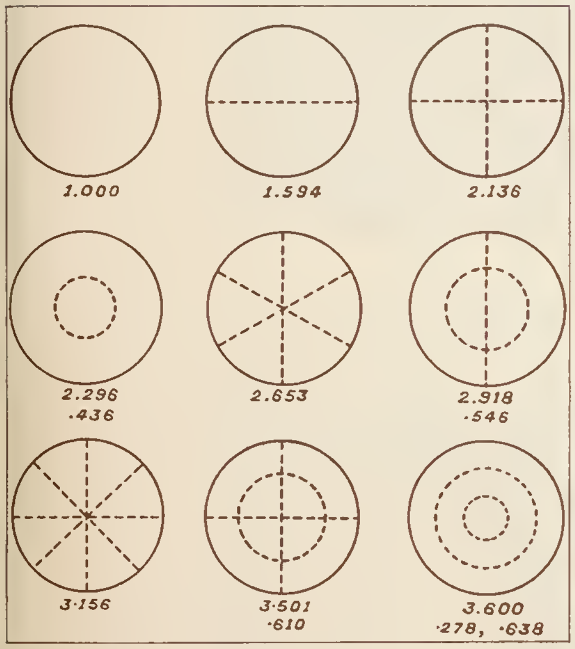
In the volume of collected papers on Acoustics by the late Prof. W. C. Sabine published recently by the Harvard University, there is a very interesting article on 'Whispering Galleries' in which the architectural and acoustical features of several remarkable structures in Europe and America have been discussed. No mention is however made of whispering galleries in other parts of the world. Among the Indian whispering galleries the most notable, architecturally and acoustically, is the great Gol Gumbaz at Bijapur. In the Victoria Memorial recently completed at Calcutta, there are two very fine whispering galleries, one of which, curiously enough, remained unsuspected till it was discovered by the writer. There is also another whispering gallery at the Calcutta G.P.O., also first noticed and studied by the writer. The acoustical properties of the building known as the Government Granary at Bankipore in Patna District are also of much interest. The present paper contains a description of these whispering galleries. Other acoustical curiosities, such as Sekundar's tomb at Fatehpur Sikri near Agra, have been brought to the writer's notice, but they are not here discussed.







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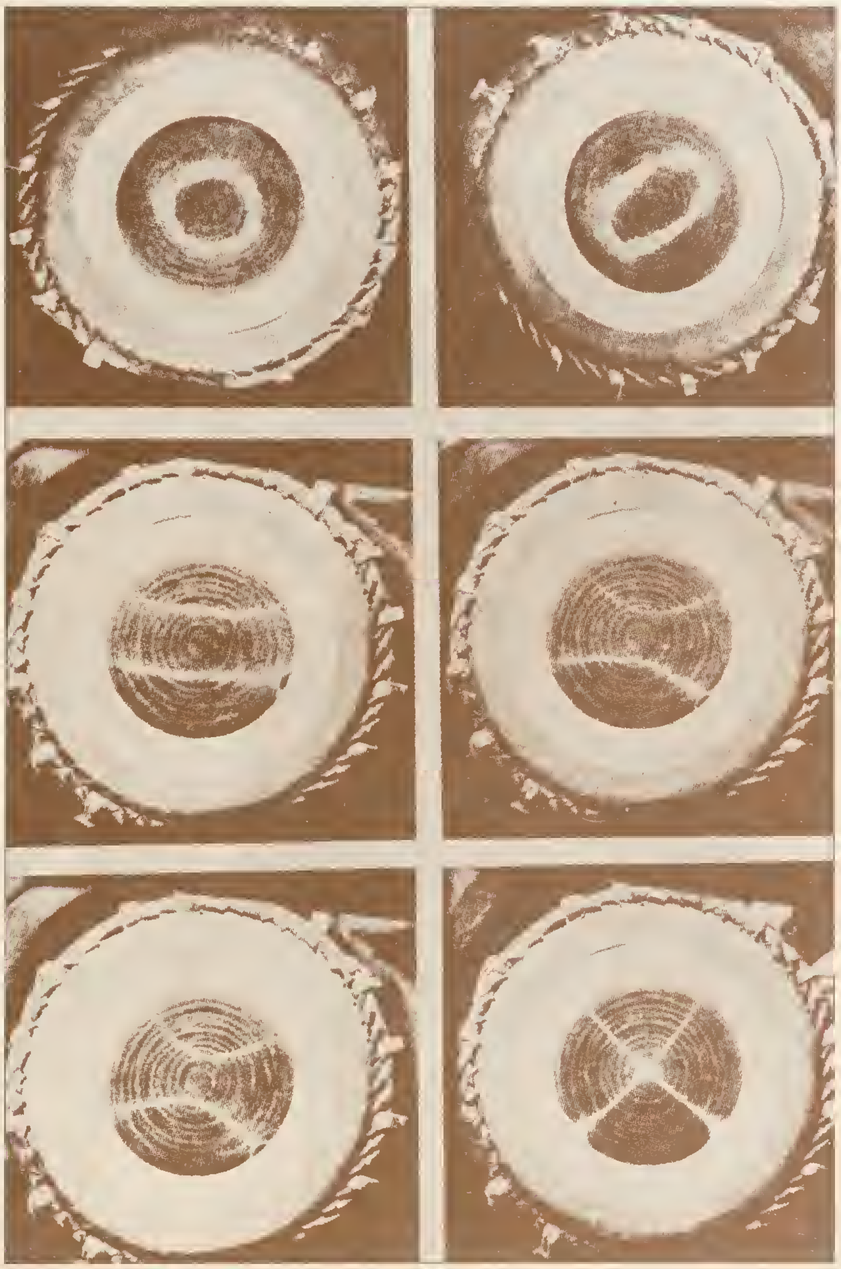

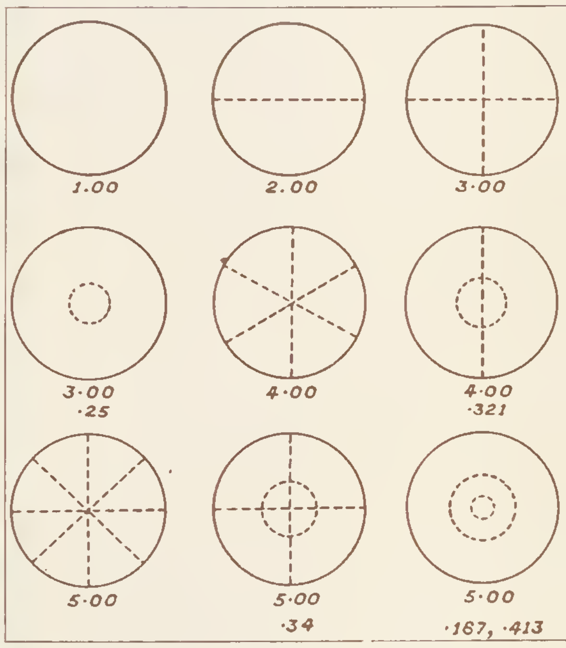
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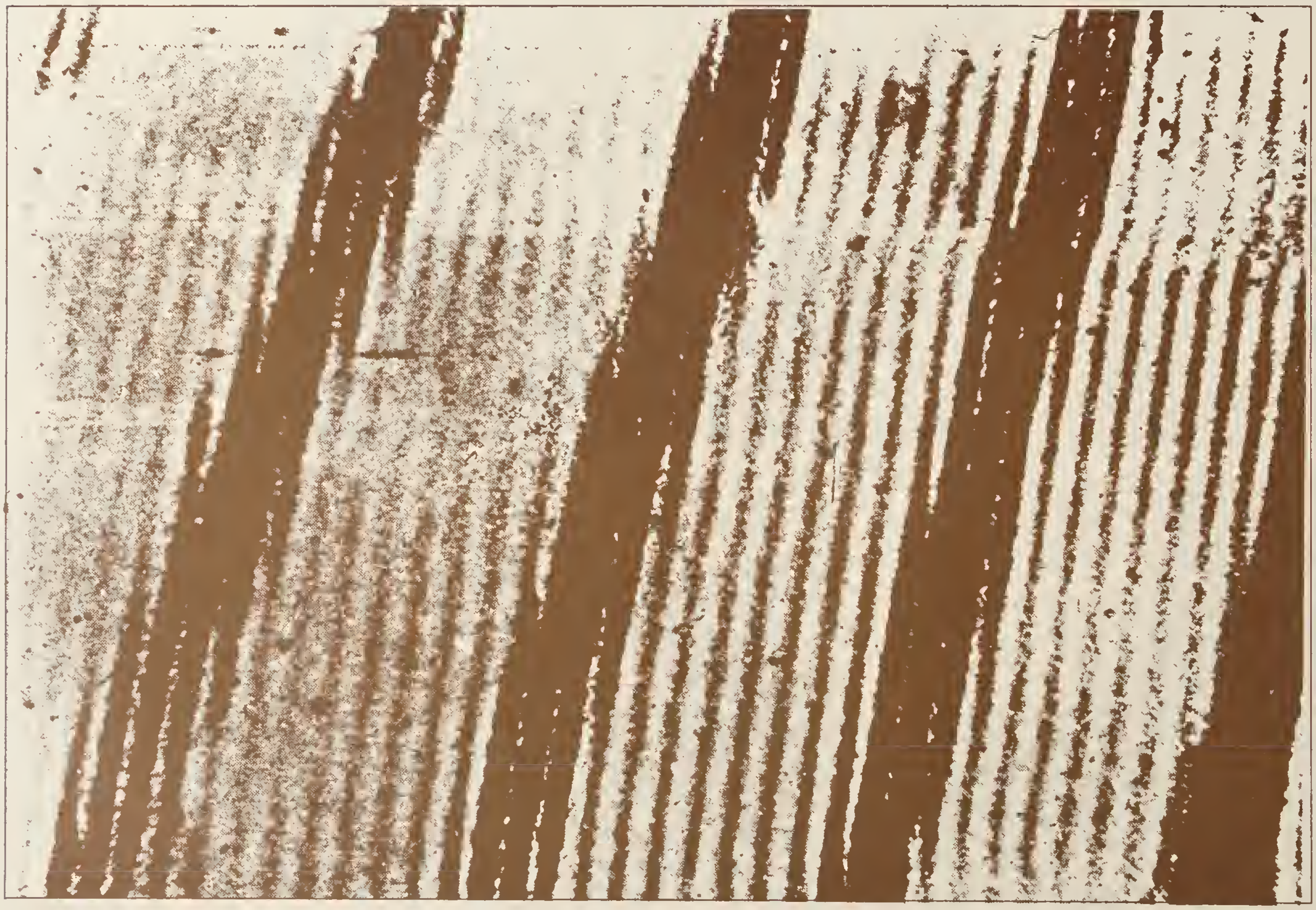
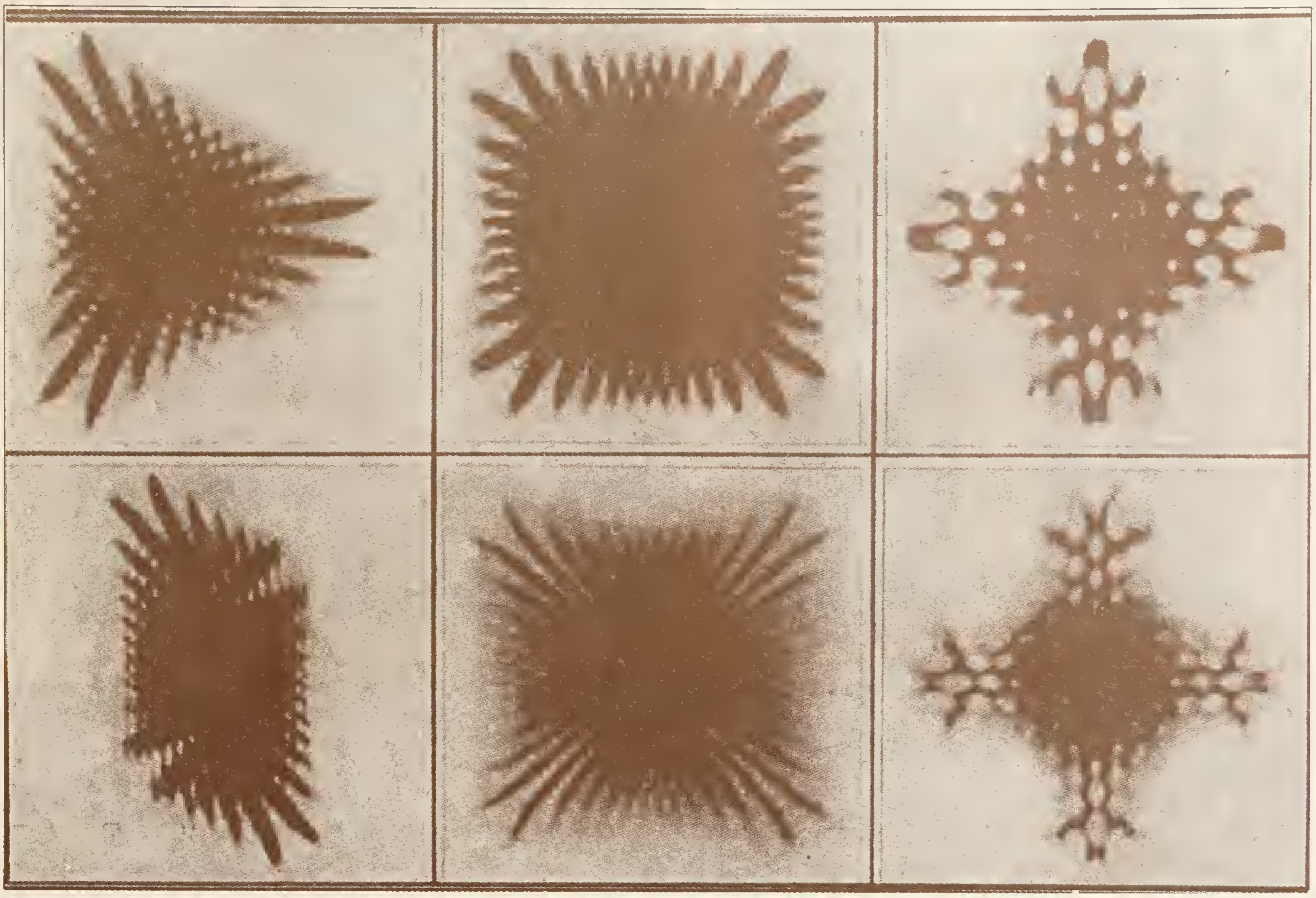
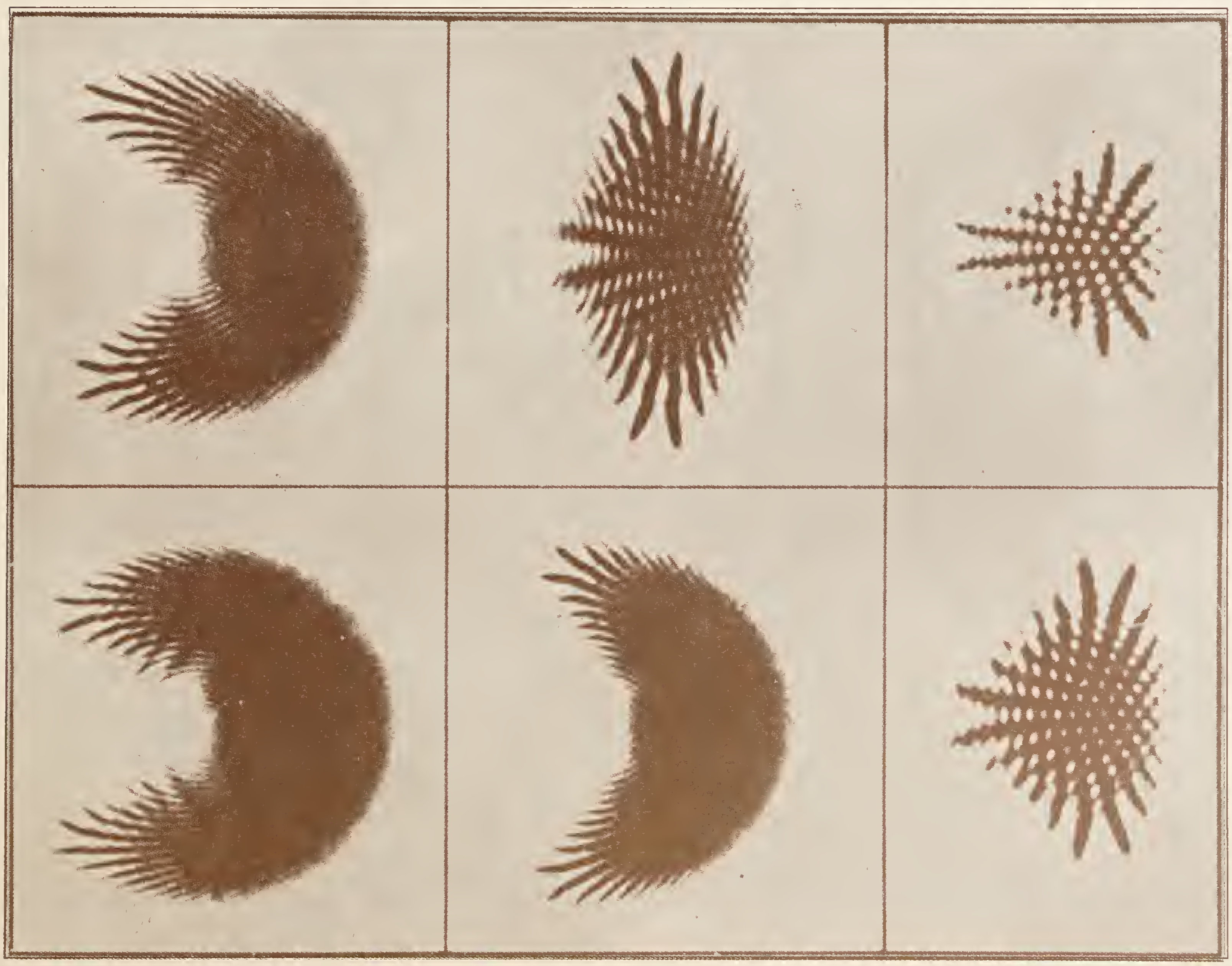
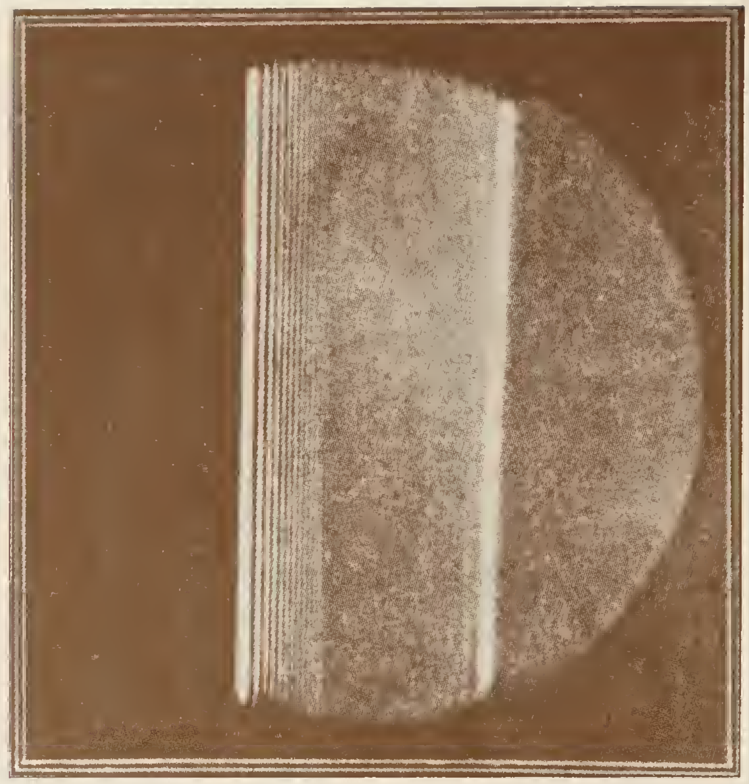
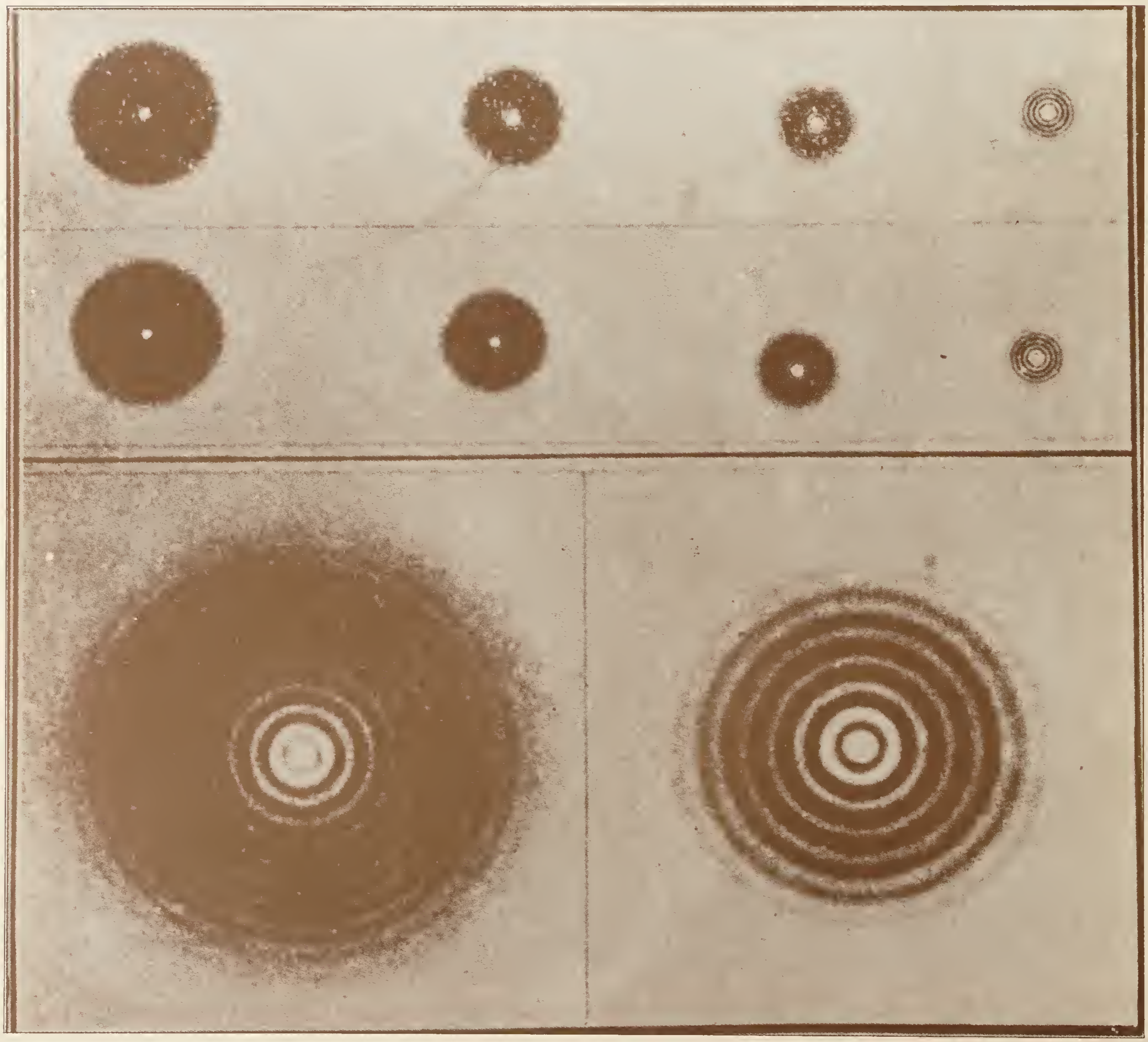




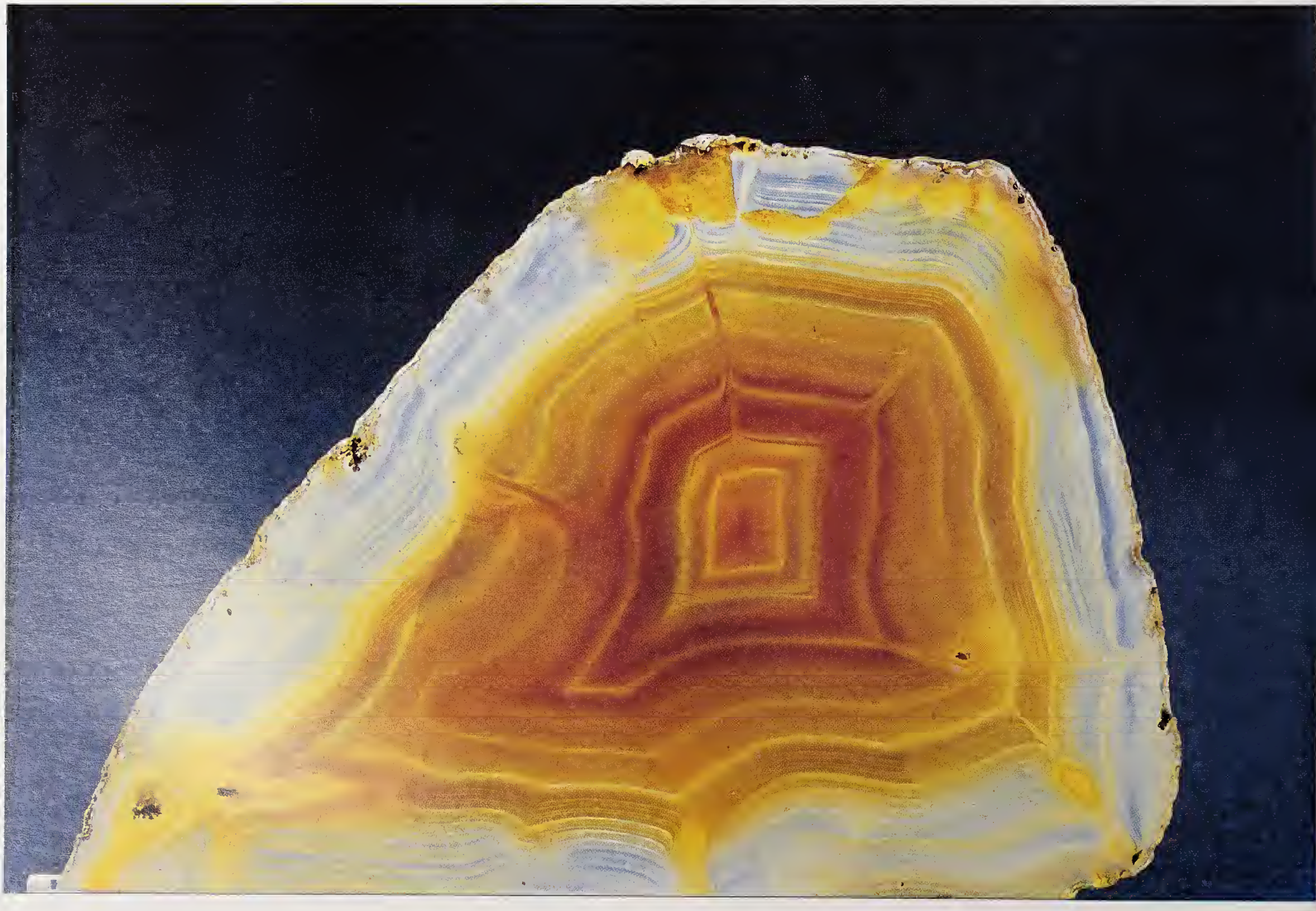


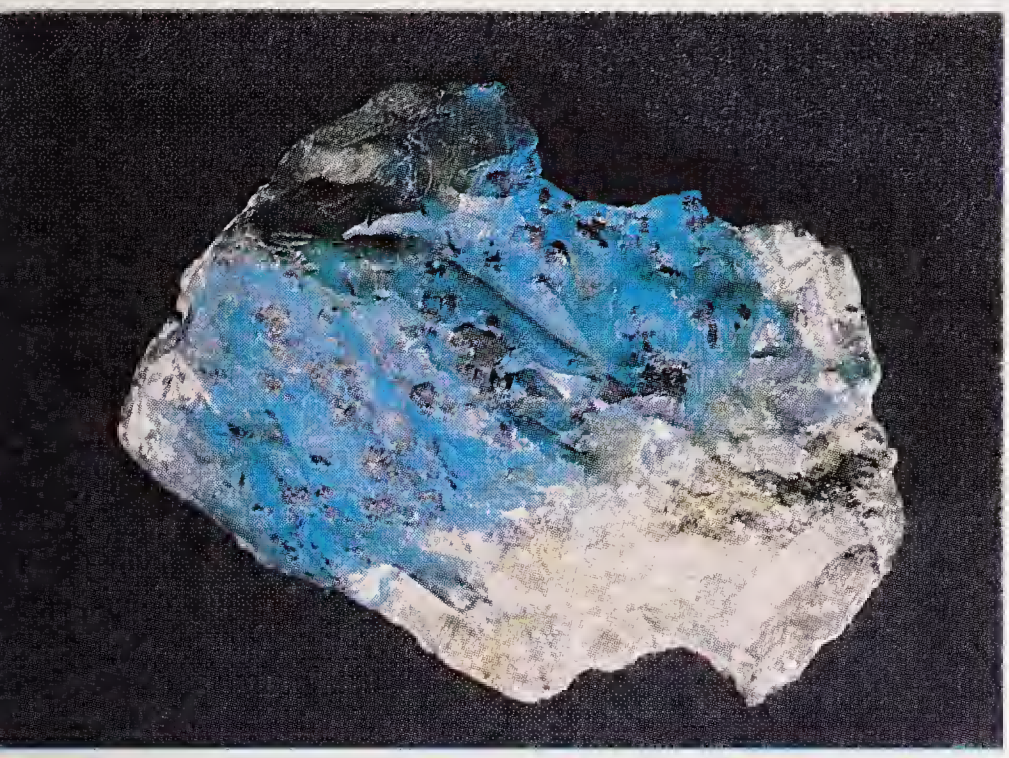


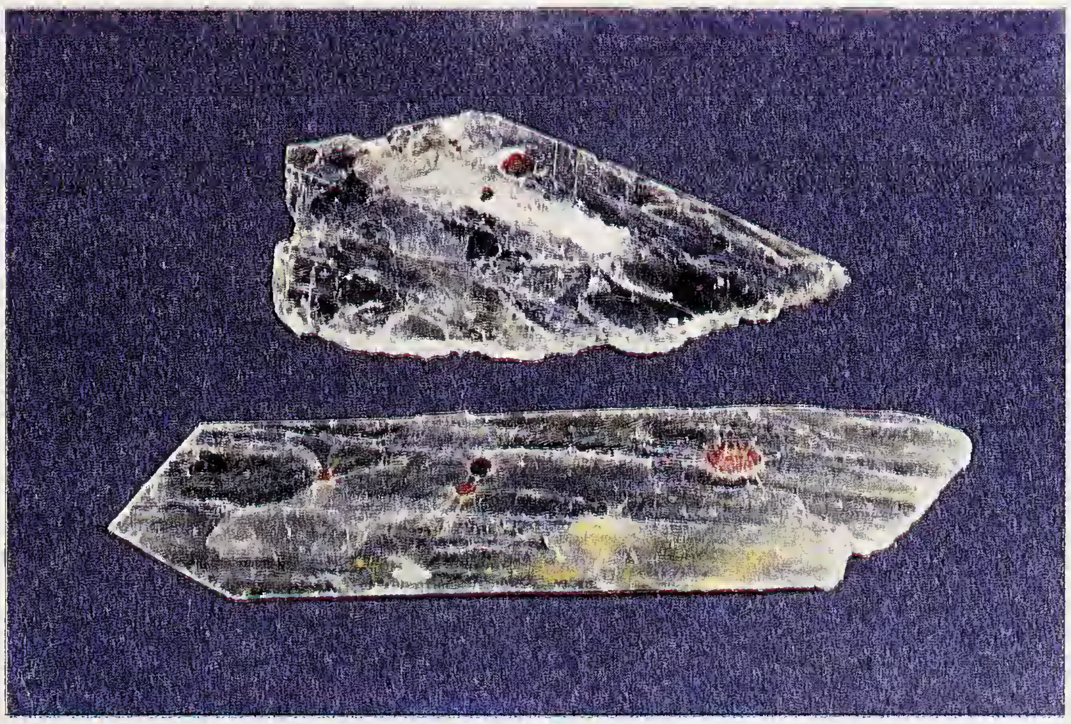



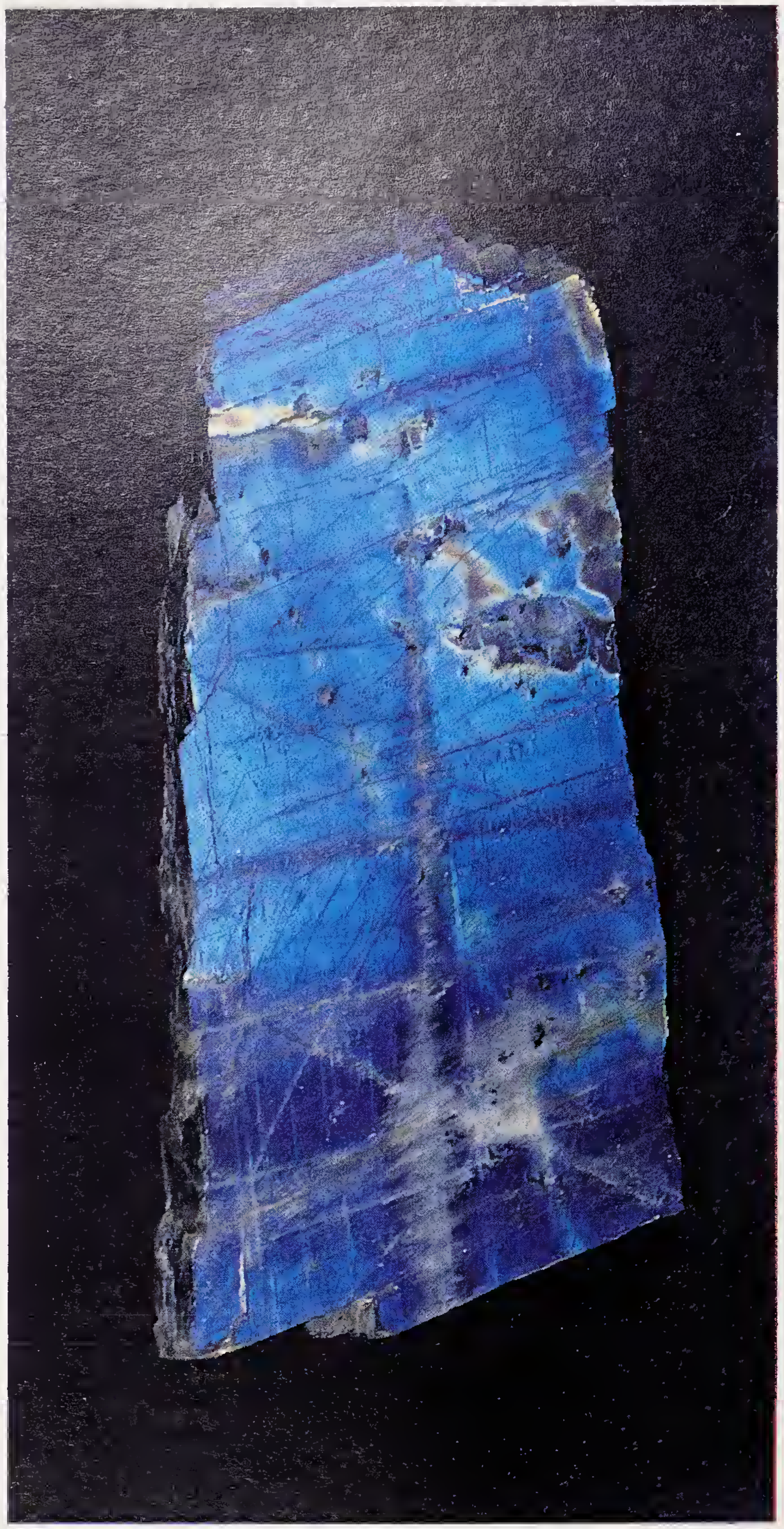
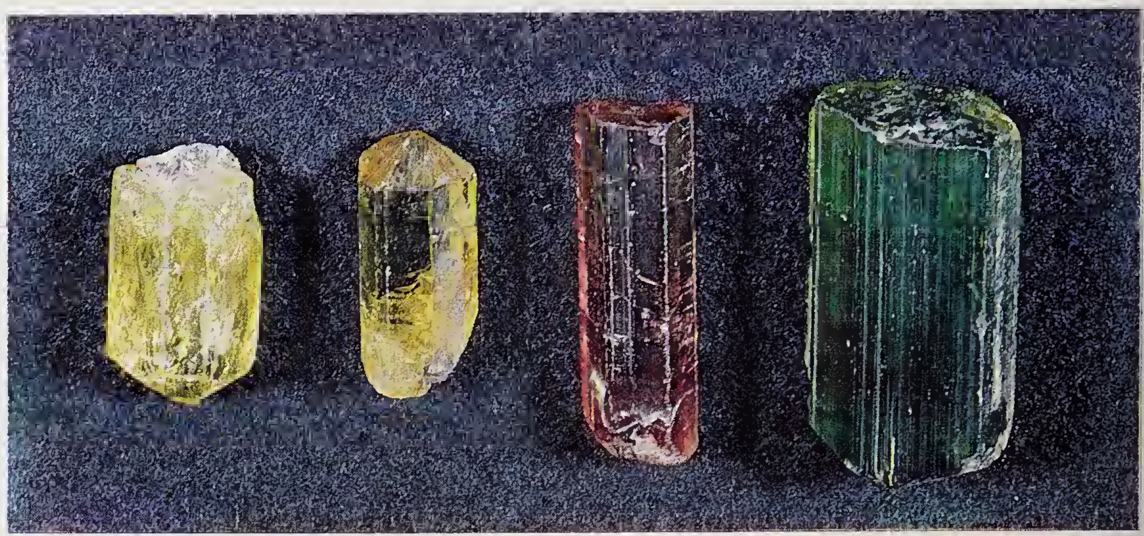
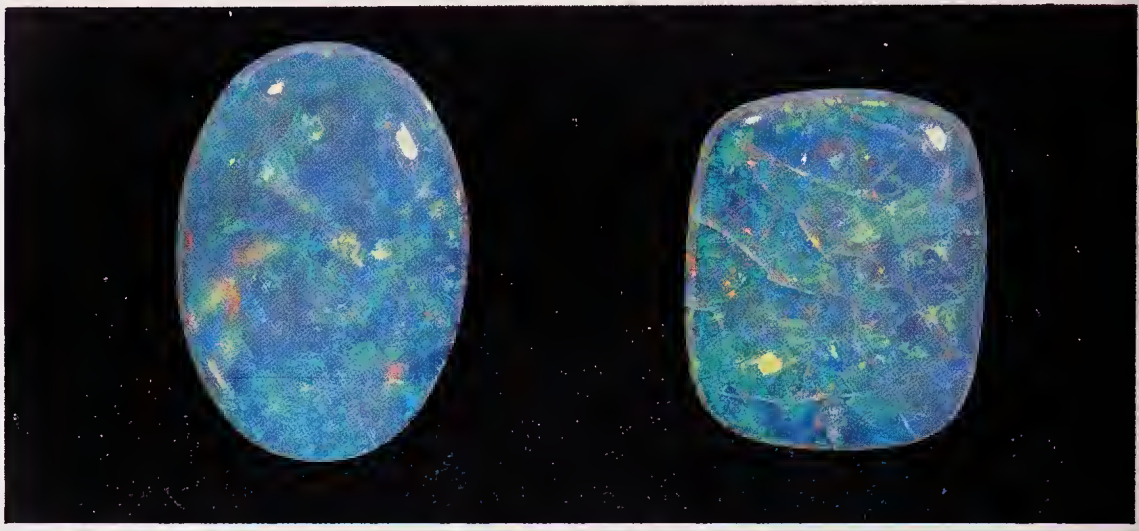
Raman's World of Colours

— Minerals, Flowers, Birds and Insects



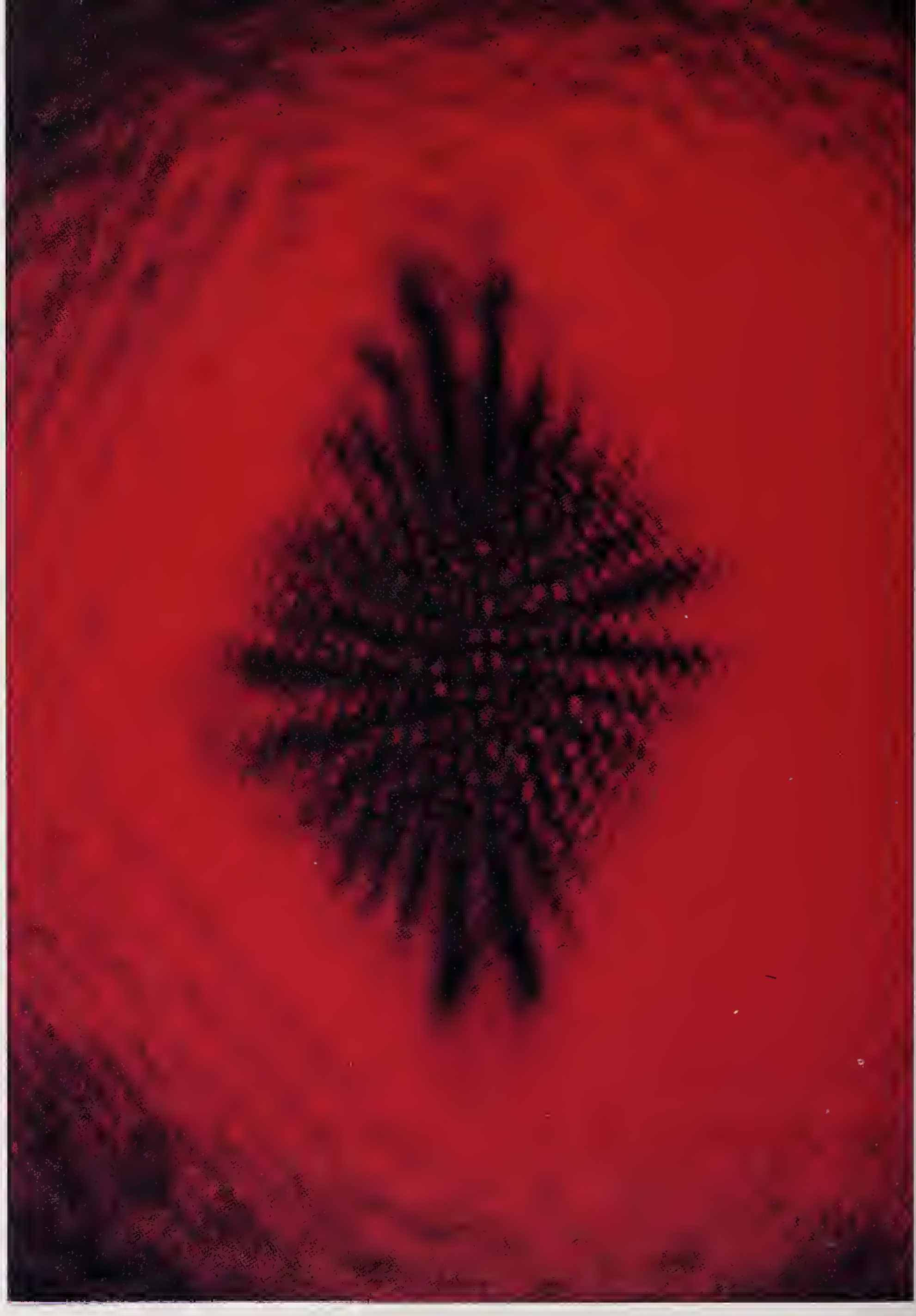
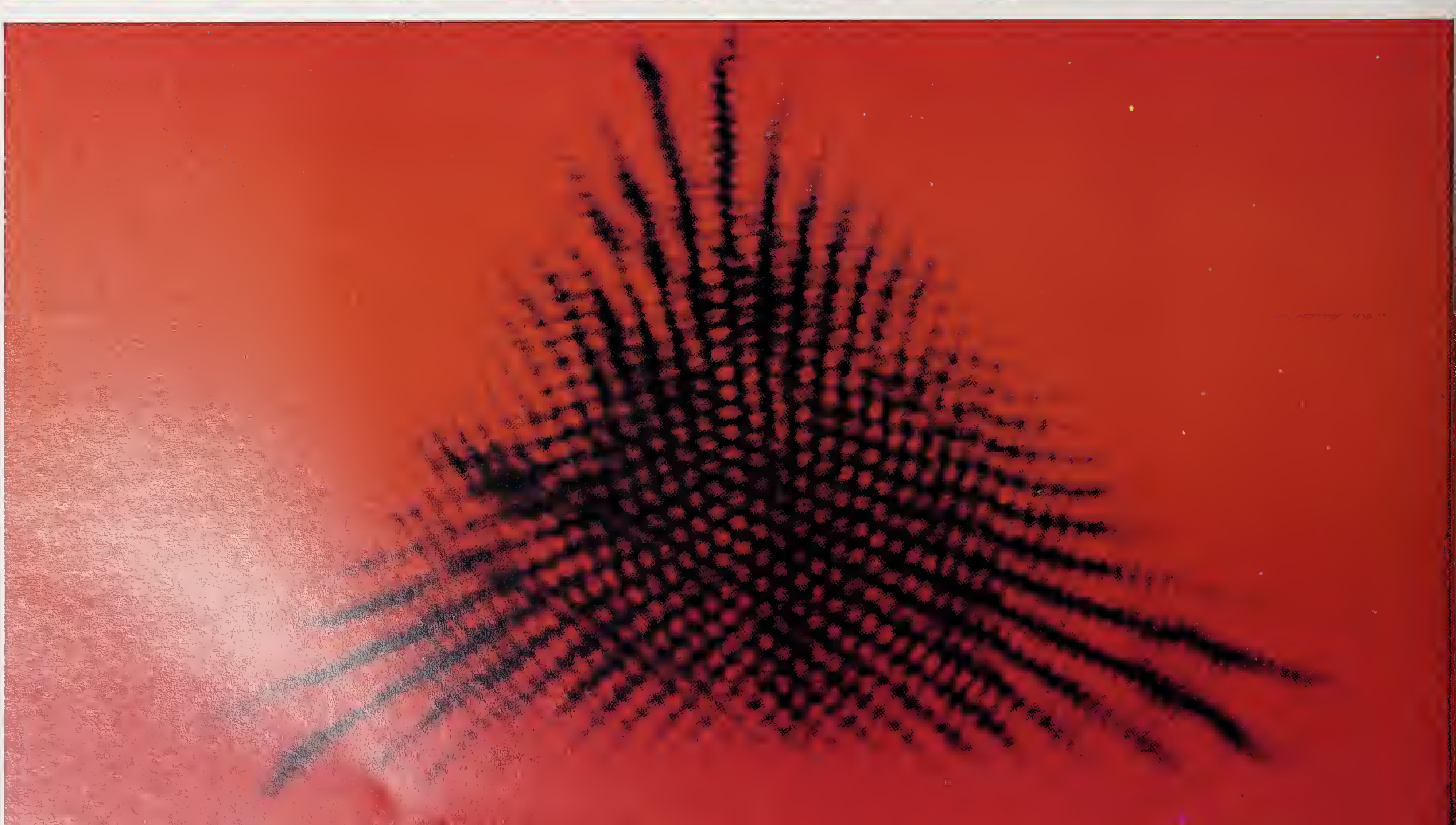




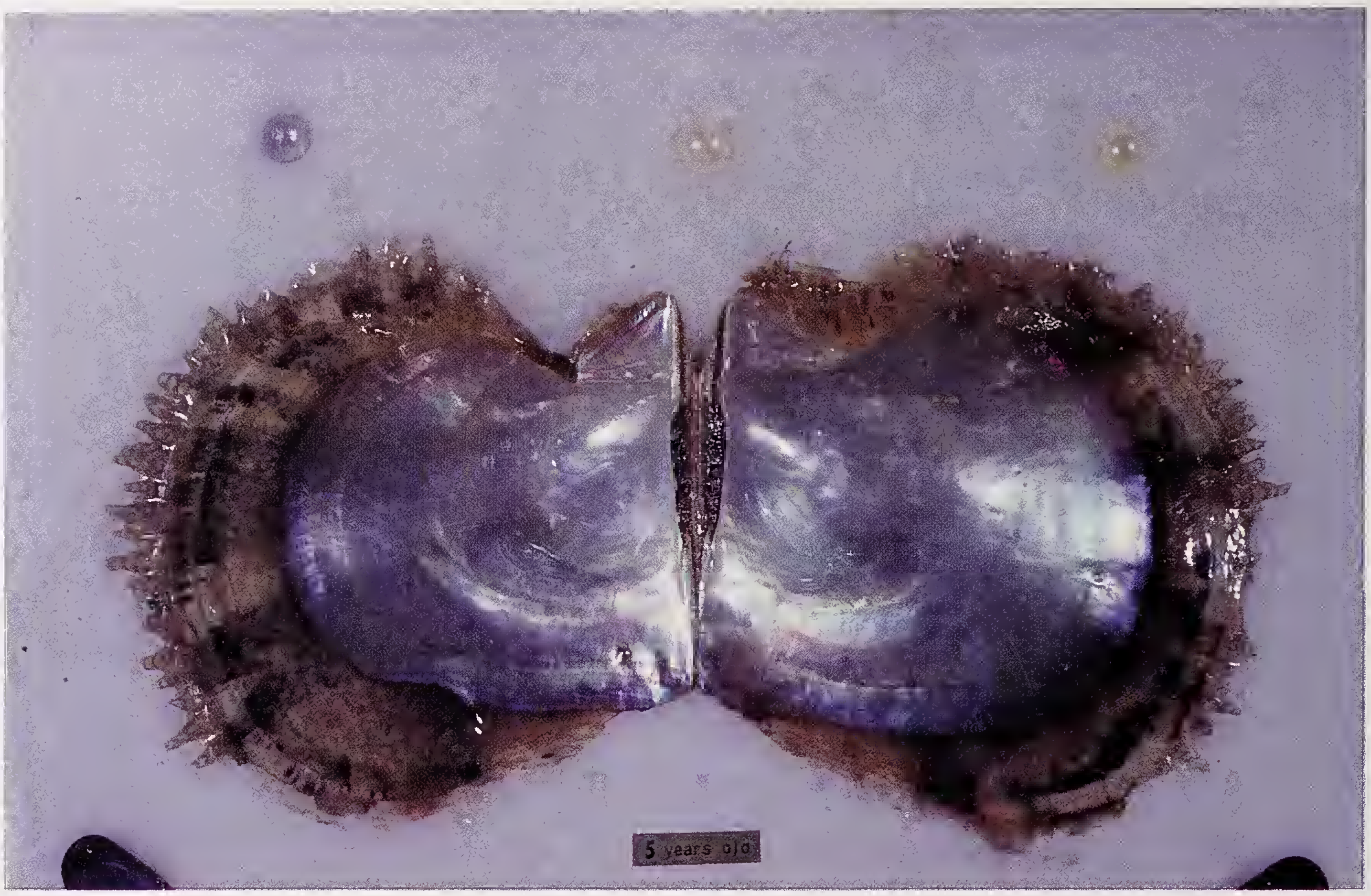








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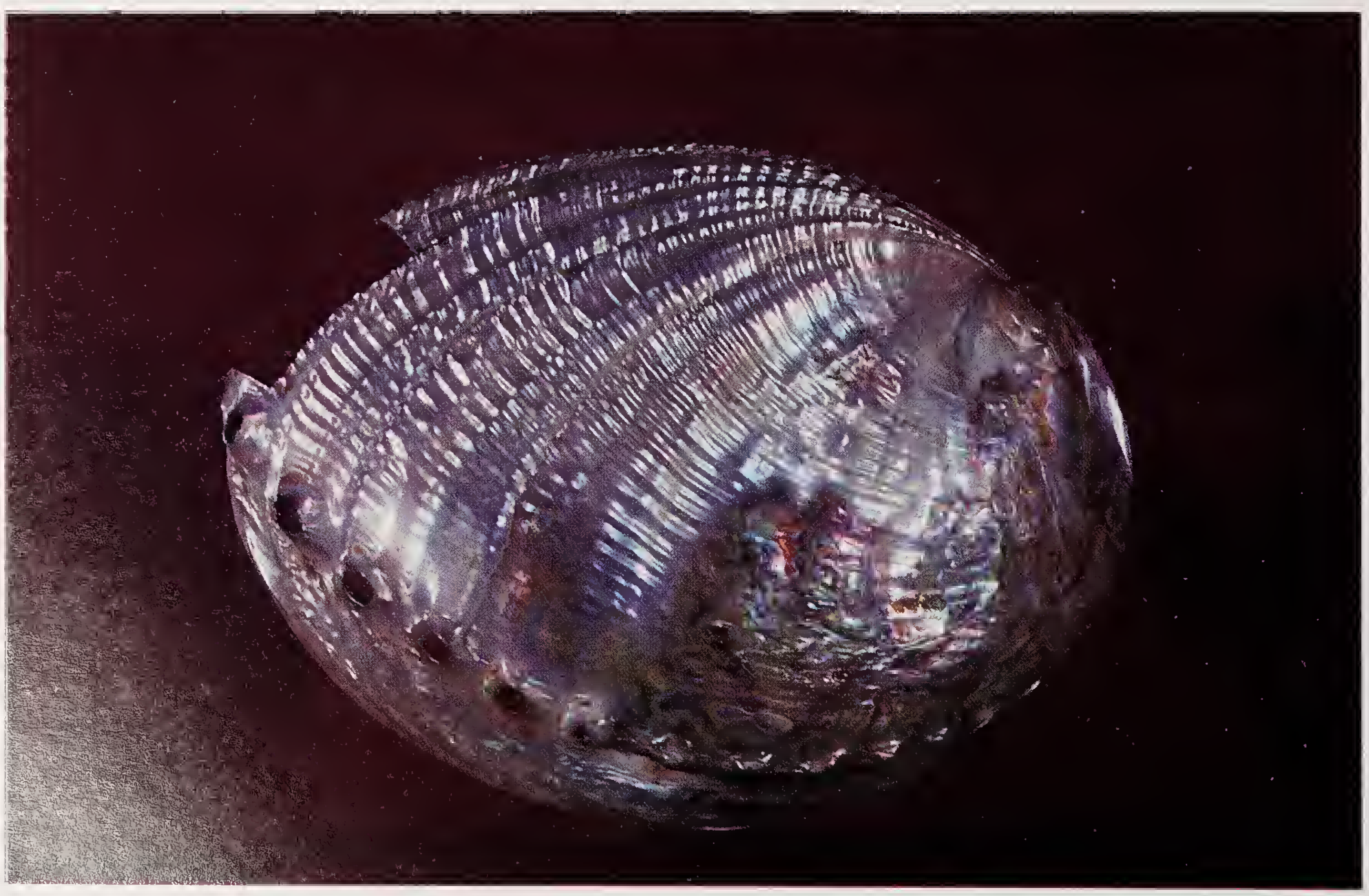


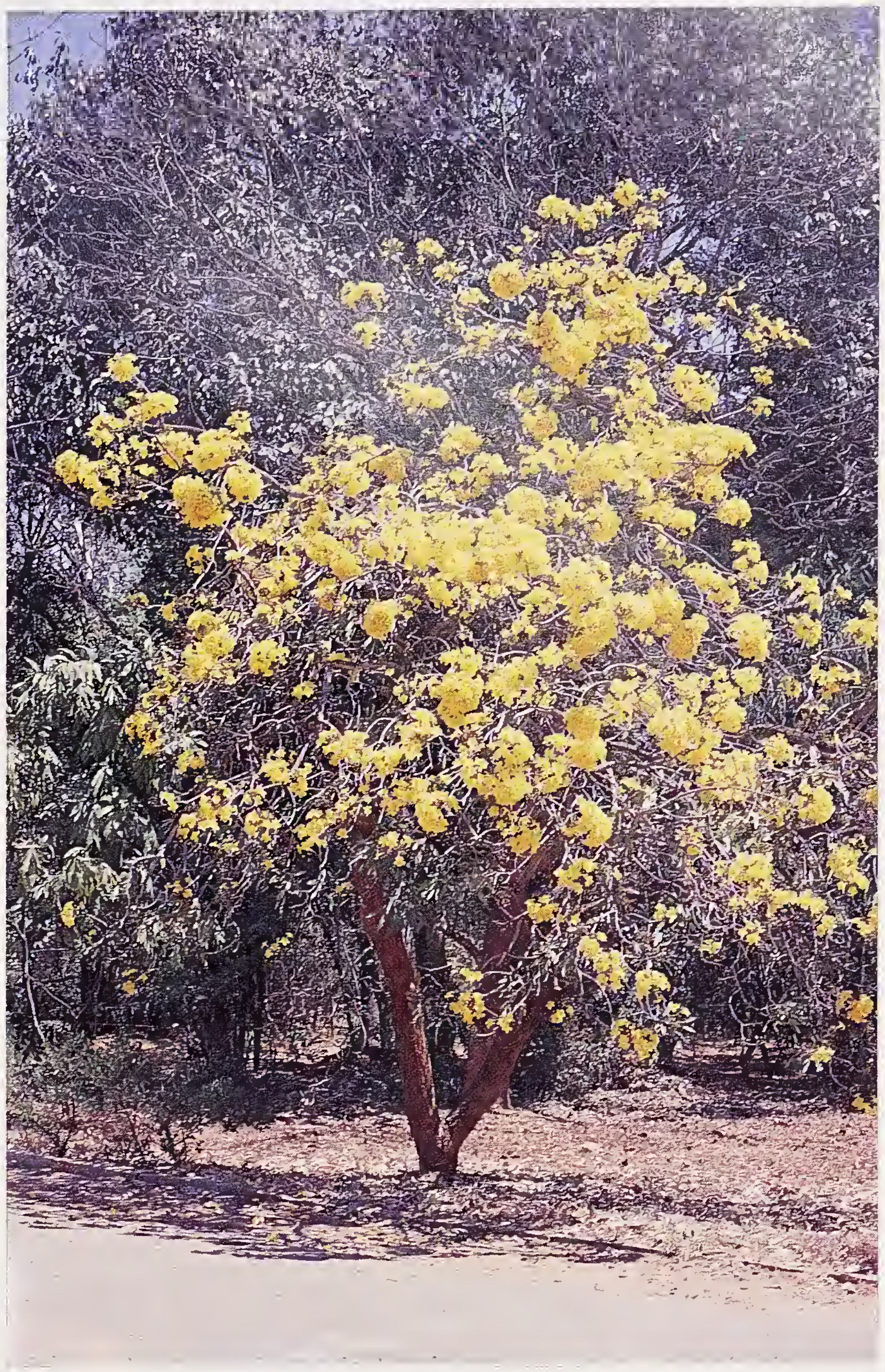


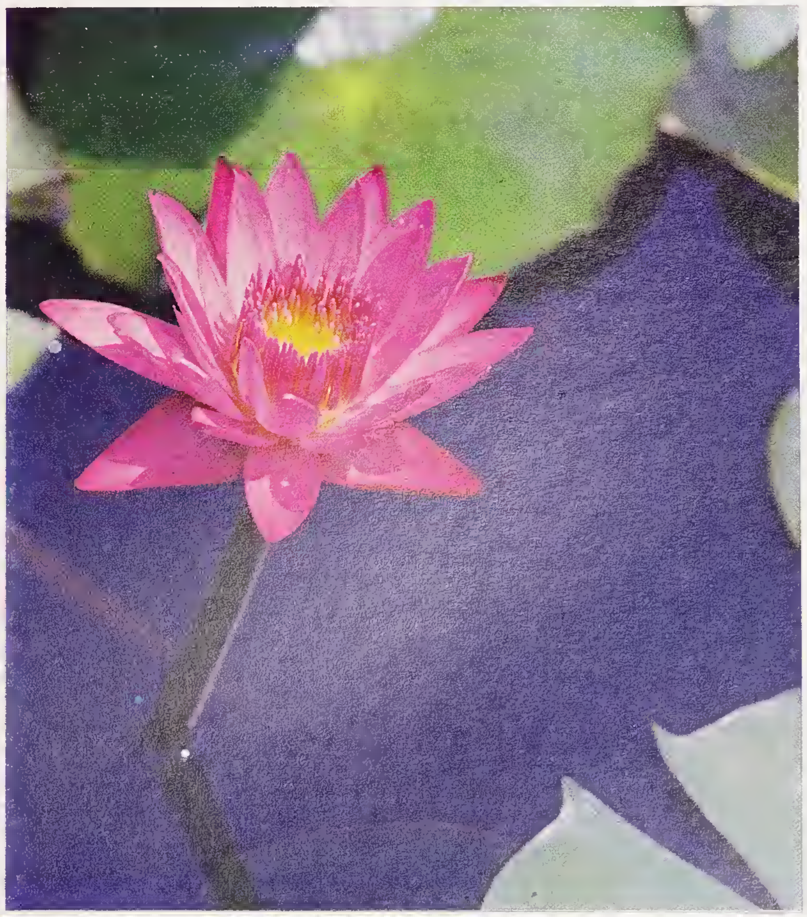





The Nobel Medal

The Nobel Diploma

The Raman Research Institute

The Lawn in RRI. The lone tree

Introduction to the Scientific Papers

SCATTERING OF LIGHT

Introduction

Chandrasekhara Venkata Raman — familiarly known to most as Sir C.V. Raman — was born on the 7th of November 1888 and died on the 21st of November 1970. During his scientific career which extended over 66 years he published more than 450 original research papers and monographs. Almost three times that number of scientific papers were published by his students, based on the work done under his direction. Volume I of the *Scientific Papers* presents 94 of the papers published by C.V. Raman, either by himself or along with his students, on the general subject of the scattering of light. In it there are papers on colloid scattering, molecular scattering, surface scattering, Raman scattering and Brillouin scattering, as also his pioneering publications on molecular anisotropy. The celebrated monograph he wrote in 1922, *Molecular diffraction of light,* and his investigations on X-ray scattering and Compton scattering have been included as these played a significant role in his discovery of the Raman effect in 1928. The classical papers he wrote on magnetic, electric and flow birefringence along with his gifted student KS Krishnan also find a place in this volume. The titles of papers published by his students and collaborators from his laboratory on light scattering have been given at the end of this volume.

In early 1904 at the age of 16, C.V. Raman, as an undergraduate at the Presidency College, Madras, commenced his experimental researches on sound and light. Lord Rayleigh's *Scientific Papers,* and *Treatise on Sound* and the works of Helmholtz were familiar to him. At eighteen he became an officer in the Finance Department of the Government of India. He did his scientific researches after hours at home or mostly in the Indian Association for the Cultivation of Science in Calcutta. His investigations were largely in the fields of acoustics, musical instruments and wave optics. The exquisite sensations of tone and the beauty of the colours arising from interference and diffraction of light fascinated him.

His first paper on the scattering of light appeared only in 1919. It was on the Doppler effect in molecular scattering. At that time he had also begun to take interest in the phenomenon of the scattering of light by sulphur suspensions. The paper on this subject makes interesting reading now, as one can see many elements in it that were to be introduced later into the Raman–Nath theory (see Volumes II and III) of the diffraction of light by ultrasonic waves.

The blue of the Mediterranean

It is definite that the intense interest he developed in the scattering of light was due to the visual impact that the blue of the Mediterranean sea made on him during his first voyage to Europe in 1921. It was not, however, the first time he saw the blue of the waters. Almost every day he must have seen the panoramic view of the famous Madras beach from his college — the Bay of Bengal in all its glory with colours ranging from a greenish yellow near the shore to an intense blue in the distance.

That he was puzzled by the problem of the colour of the sea is clear from the fact that even on his onward journey he had prepared himself well for experimental observations; for he carried in his pocket nicol prisms, a small telescope to which polarisers and analysers could be attached, a slit and even a diffraction grating.

He wrote two papers on board the ship (SS *Narkunda*) on which he returned to India. The one entitled 'The colour of the sea' questioned the validity of the view expressed by Lord Rayleigh that the much admired dark blue of the deep sea was simply the blue of the sky seen by reflection. While on the Mediterranean and the Red seas Raman quenched the surface reflection by a nicol prism and noticed that the colour of the sea

was by no means impoverished by this, but actually improved wonderfully. Using the diffraction grating he showed that the maximum spectral intensity differed in the case of the blue sky and that of the blue sea. He suggested that the local fluctuations in density postulated by Einstein and Smoluchowski should not only explain the scattering of light in liquids but also in solids. He proceeded to make measurements on water and crystalline quartz and showed that this was indeed true. He also examined amorphous substances and proposed that the intense scattering of light by these was due to the *permanent* local fluctuations in density similar to those that arise transitorily in liquids. He climbed the summit of Mount Doddabetta in the Nilgiris (to avoid the dust haze), measured the depolarization of light scattered by the sky and ascribed the residual depolarization to molecular anisotropy.

Molecular diffraction of light

To clarify his own views he wrote a monograph, *Molecular diffraction of light*. He dedicated it to the enlightened Vice-Chancellor of the Calcutta University Sir Asutosh Mookerjee who had made Raman a full-time scientist by offering him the Palit Chair of Physics. The monograph bristles with ideas, but it is obviously hastily written. It is said that it was written, printed and published during the course of seven weeks. In this volume Raman examines the molecular scattering of light by gases, by the atmosphere, and by liquids. The colour of the sea, the albedo of the earth, scattering of light in crystals and in amorphous solids occupy his attention. He deals with the problem of the Doppler effect in molecular scattering—a topic he was to come back to in later years.

In the concluding chapter of this essay entitled 'The scattering of light and the quantum theory' he tries to understand the mechanism of light scattering. By imagining molecular scattering to take place in a black-body enclosure Raman had convinced himself that Rayleigh scattering must also occur in a discontinuous manner.

He then points out that if the process of scattering could be regarded as a collision between a light quantum localized in space and an individual molecule, the observed laws of light scattering would be different from that anticipated on the classical principles of an electromagnetic theory of light. He makes reference to cases in which the classical wave theory seems to fail to explain the facts relating to molecular scattering in a satisfactory manner. In fact Raman was convinced that accurate measurements on the scattered light would bring out these contradictions. The review of the monograph in *Nature* in 1922 mentions: "Prof. Raman makes the interesting suggestion that the failure may mean that the continuous wave theory of light does not strictly represent the facts and that we may perhaps find experimental support for the Einstein conception that light itself consists of quantum units."

To the historian of science, there is one paragraph in this monograph which is of interest:

> The belief in the validity of Newtonian dynamics applied to the ultimate particles of matter has, however, received a rude shock from the success of the quantum theory as applied to the theory of specific heats, and there seems no particular reason why we should necessarily cling to Newtonian dynamics in constructing the mathematical framework of field-equations which form the kernel of Maxwell's theory. Rather, to be consistent, it is necessary that the field-equations should be modified so as to introduce the concept of the quantum of action. In other words, the electrical and magnetic circuits should be conceived not as continuously distributed in the field but as discrete units each representing a quantum of action, and possessing an independent existence.

These words were written in early 1922. The programme suggested here of quantizing the electromagnetic field was commenced by Dirac in 1928.

Students, many of whom were university teachers (who came as vacation workers), were put on problems connected with the scattering of light. In 1923 the study of the scattering of light in water was taken up by KR Ramanathan. Sunlight was focussed on the liquid contained in a flask and the scattered light was seen as a track in the transverse direction. Even from the beginning, Raman's intuition seems to have told him to look for a change in colour in scattering. By the proper use of a system of complementary filters a "weak fluorescence" was detected in the scattered track. This was attributed to impurities in the liquid. Ramanathan wrote much later: "Raman was not satisfied with the explanation that it was due to fluorescence. He felt that it was characteristic of the substance and wondered whether it might not be akin to the Compton effect in X-ray scattering [which had just been discovered that year]". At the insistence of Raman, the liquid was purified again and again but the effect persisted. The "weak fluorescence" also showed polarization effects but Raman, for some strange reason, did not

follow up this important clue as he did later in 1928. In 1924 the "weak fluorescence" was again observed by K S Krishnan and in 1925 Raman asked S Venkateswaran to try to obtain a spectrum of this "weak fluorescence" but no spectrum could be recorded. Raman saw this "feeble fluorescence" as a *disturbing effect* superposed on the classical scattering of light.

X-ray diffraction and Compton scattering

It is interesting that Compton too attributed the softening of X-rays by scattering to what he called a "general fluorescent radiation" almost in the manner Raman labelled the phenomenon he observed as "a special type of feeble fluorescence". Because of the close analogy with the Compton effect Raman became interested in X-ray scattering again.

Raman (along with Ramanathan) had broken new ground in the field of X-ray scattering in liquids in 1923. He showed that scattering at very low angles was governed by the Einstein–Smoluchowski fluctuations. For explaining the scattering at larger angles the discrete structure of the medium must be taken into account. For this the distribution of matter in the fluid must be analysed into a continuous "structural spectrum" which has its peak of intensity at a wavelength equal to the mean distance between the neighbouring molecules. Raman once said, "We were so preoccupied with light scattering that we did not apply the idea of Fourier transforms to X-ray scattering of liquids although we were so close to it". This was done later in 1927 by Zernicke and Prins.

Raman attempted to understand the Compton effect from the point of view of the classical wave theory. In this process he derived what is now known as the Raman–Compton formula. It was then that the true nature of the "feeble fluorescence" phenomenon became evident to him. The Compton effect could be considered as due to a kind of "fluctuation" in the state of the scattering atom in the field of the radiation. If much milder fluctuations were possible they should give rise to a change in wavelength in the light scattered by the molecule. He was more convinced than ever that the "weak fluorescence" phenomenon was the optical analogue of the Compton effect.

The Raman effect

So he pressed on with the experimental study of this phenomenon. S Venkateswaran, a part-time worker in his laboratory, succeeded in purifying many organic liquids by slow distillation *in vacuo* and observed a greenish-blue track in pure glycerine and the fluorescence was *strongly polarized*. This clearly indicated to Raman that the phenomenon could not be the conventional fluorescence—a point of view he had always taken and for which he was seeking proof. Venkateswaran was a part-time worker who could only work after working hours and on holidays. Raman wanted someone to use the sunlight available all through the day, particularly as he himself had lecturing commitments at the University. And so he pursuaded KS Krishnan, the best student he had at that time, to get on to these experiments. With KS Krishnan, Raman observed that all the pure organic liquids available in the laboratory showed this "feeble fluorescence" and he was convinced that this was the modified scattering of altered wavelength corresponding to his "milder fluctuations" in the state of the scattering molecule and in fact due to the Kramers–Heisenberg process. The real discovery of the Raman effect took place on the 28th of February 1928 when Raman pointed a direct vision spectroscope on the scattered track and saw that the scattered light contained not only the incident colour but at least one other, separated by a dark space.

Filtered sunlight, which till then had been used as the incident light, was replaced by a quartz mercury arc and sharp modified Raman lines were recorded. The shifts in frequency were identified with some of the characteristic infra-red frequencies of the molecule. Not only the degradation but also the enhancement of the frequency of the scattered radiations was observed. Scores of papers were published by his students on Raman scattering. Before long many laboratories round the world also took up the study of the Raman effect, particularly in simpler molecules. But in Raman's laboratory the accent was on the study of more fundamental problems connected with the physics of the solid and liquid states.

Spin of the photon?

Even in their earliest photographs, Raman and Krishnan noticed an asymmetric nebulosity accompanying the spectral line of the incident radiation when scattered by liquids. This they suggested was the effect of those collisions of the incident light quanta with molecules which result in a change of their rotational state. We include in this volume four later papers by Raman and Bhagavantam on the experimental and theoretical investigations of the wings of the Rayleigh line. They found that, even on increasing the spectral resolution as far as possible, the depolarisation ratio of the central line to the entire Rayleigh line did not fall to the

value of one–fourth predicted by the Kramers–Heisenberg formula. The authors were, of course, aware that stray light, instrumental polarization, imperfect spectral resolution would all tend to increase the measured depolarization of the central component. Nevertheless, Raman and Bhagavantam attributed the discrepancy to a new effect arising from the spin of the photon which (they felt) was not included in the semi-classical radiation theory.

However, we now know that the search for an effect lying entirely outside the province of the semi-classical theory did not end till the late 1940's when the Lamb shift and the deviation of the electron *g*-factor from 2 were discovered.

Optical and magnetic anisotropy

Raman's interest in optical anisotropy led him on to study magnetic anisotropy, and then to the magnetic properties of molecules. He was amongst the earliest to explain the anomalous diamagnetic susceptibility in graphite and the high diamagnetic anisotropy of aromatic organic compounds as due to electron orbits of large area including several atoms within their radius. The lecture at the Physical Society, London, summarises much of the work done in Calcutta by Raman's school on magnetism and magnetic properties.

Shear modes in liquids

The Doppler effect in molecular scattering intrigued Raman even in 1919. He was attracted by the theory of Brillouin that the medium which scatters radiation can be treated as a continuum filled with moving high–frequency sound waves of various wavelengths which reflect the light rays in the same manner that a moving crystal would give Bragg reflections of X-rays. Raman showed that (as in Compton scattering) Brillouin scattering can only take place when both the energy and the momentum equations are satisfied. Even in the monograph of 1922 Raman had suggested an experimental technique for studying the Doppler effect in light scattering. Using a similar set-up with a Fabry–Perot etalon, the Brillouin scattering was observed in many liquids, and Raman discussed the paradox of the appearance of the central component. The velocities of the "hypersonic" waves in these liquids were determined. Perhaps the most exciting result obtained by Raman and his collaborators in the field is that viscous liquids at these high frequencies behave like amorphous solids capable of sustaining both longitudinal and transverse waves.

His studies in Brillouin scattering made Raman reconsider the thermodynamic theory of light scattering. Einstein considered the density fluctuations to be static and isothermal while in the theory of Brillouin they are considered to be dynamic stratification of sound waves and therefore presumably adiabatic in character. To test this, the adiabatic piezo-optic coefficients of some common liquids were measured. Using these experimental values and assuming the density fluctuations to be adiabatic in character, the intensity of scattering was calculated. The observed intensities were found to support the adiabatic hypothesis.

Discovery of the "soft mode"

Raman (together with Nedungadi) published a beautiful paper on 11 December 1939 on the alpha–beta transformation of quartz. As the temperature was raised it was noticed that the 220 cm^{-1} line in the Raman spectrum behaved in an exceptional way, spreading out greatly towards the exciting line and becoming a weak diffuse band as the transition temperature was approached. On the other hand the other intense lines, having both larger and smaller frequency shifts, continued to be easily visible, though appreciably broadened and displaced. Raman conjectured that "the binding-force which determines the frequency of the corresponding mode of vibration of the crystal lattices diminishes rapidly with rising temperature". He inferred that "the increasing excitation of this particular mode of vibration with rising temperature and the deformations of the atomic arrangement resulting therefrom are in a special measure responsible for remarkable changes in the properties of the crystals already mentioned, as well as for inducing the transformation from the alpha to the beta form". Almost twenty years later this effect was rediscovered and is now known as the "soft mode".

We have contented ourselves, in this introduction, with making a few historical comments, and now leave the vigour and lucidity of Raman's papers to speak for themselves.

ACOUSTICS

Introduction

Raman commenced his acoustical researches at the age of 16 as a student of the Presidency College, Madras. Volume II of the *Scientific Papers* contains articles he published in acoustics, either by himself or along with his students. Fifty-three papers cover the fields of vibrations and wave motion, whispering gallery phenomena, bowed strings and the violin, the musical instruments of India and the diffraction of light by ultrasonic waves. This volume also contains two monographs Raman wrote, both classics. The first is entitled *On the mechanical theory of the vibrations of bowed strings and musical instruments of the violin family*. The second, *Musikinstrumente und ihre Klange,* appeared in 1927 in the *Handbuch der Physik* edited by Geiger and Scheel. This article was written by him in English but was published as a translation in German. Since all attempts to get at the original English version were unsuccessful, an English translation of the German version appears in this volume. Raman also published a series of papers on the phenomena connected with impact, which has some relevance to the vibrations of struck strings. These are included in Volume IV of the *Scientific Papers* in the Miscellaneous section.

In this introduction, we shall content ourselves with making a few historical remarks and scientific comments on the papers appearing in this volume.

C.V. Raman's father, R Chandrasekhara Iyer, a teacher of physics and mathematics, was a man of accomplishment. He had a remarkable collection of books on varied subjects and he was also a proficient violinist. These must have influenced Raman as a child (Raman himself also became a competent violin player). Before he was 13, Raman read Hermann von Helmholtz's *Popular lectures on scientific subjects* from his father's library. Two of the lectures made a lasting impression on him. The first was "Ice and glaciers", delivered at Heidelberg in 1865, in which Helmholtz says:

> In the depths of the crevasses, ice is seen of a purity and clearness with which nothing that we are acquainted with in the plains can be compared. From its purity it shows a blue like that of the sky, only with a greenish hue.

Raman mentions this in his well-known paper "The colour of ice in glaciers" (see *Scientific Papers,* Volume I) where he proved that this blue was due to molecular scattering. The second was the lecture delivered in Bonn, the native town of Beethoven, entitled "The physiological causes of harmony in music". Helmholtz's influence on Raman is seen by what he wrote later:

> It was my good fortune, while a student at college, to have possessed a copy of an English translation of his great work *The sensations of tone.* As is well known this is one of Helmholtz's masterpieces. It treats the subjects of music and musical instruments not only with profound knowledge and insight, but also with extreme clarity of language and expression. I discovered the book myself and read it with the keenest interest and attention. It can be said without exaggeration that it profoundly influenced my intellectual outlook. For the first time I understood from its perusal what scientific research really meant, and how it could be undertaken.

Here is probably the answer to the enigma of why a 16-year-old boy started doing research at a place where there was no tradition of original research in physics. No wonder too that the earliest acoustical research Raman started at the Presidency College in 1905 was connected with the vibration curves of a bowed string, a field pioneered by Helmholtz and to which Raman himself later contributed so much. Raman's first acoustical paper was

published only in 1909 and it was on a musical instrument called the *ectara* (used by the poorer itinerant musicians of India) which had very distinctive acoustical properties.

As a student (1902–1904) Raman mastered Lord Rayleigh's two-volume work, *Theory of sound,* which laid the foundation for all his subsequent work in acoustics. The Presidency College in those days did not subscribe to scientific journals but the Connemara Library near Egmore did. Raman as a student of 15 regularly bicycled to this library to read the latest scientific papers of Lord Rayleigh and others.

Finance Department—sounds of impact

With no possibility of a job in the research field, Raman appeared for and topped the list in the examination that chose civil servants for the Finance Department of the Government of India. At 18 he became the youngest Assistant Accountant-General in India. One would have thought that with this his research career would have come to an end. In spite of his being posted to out-of-the-way places like Nagpur in the Central Provinces and Rangoon in Burma, he continued his scientific work carrying his laboratory in his travelling bag from town to town. In a paper sent in 1910 for publication from Nagpur he writes:

> Onc source of light was a horizontal slit and the other a vertical slit placed immediately behind the oscillating wire. Both were illuminated by sunlight.

Of course it was his young wife who stood in the hot mid-day sun on Sundays adjusting the plane mirror to illuminate the said slit system while Raman shouted instructions to her from inside the bathroom, temporarily converted into a dark room. One could never believe that the elegant vibration curves reproduced in this paper were taken under these adverse conditions!

Of some interest are also the observations he made during this period (1907–1911) on the aerial waves generated by impact which he never published. Lord Rayleigh had shown that the sound emitted when two bodies impinge on each other could not be due to vibrations of the entire body as it would be at a frequency too high to be audible. Raman concluded that sound could not also be due to the compression of air between the two objects, for in that case the sound would be loudest across the line of impact of the balls. His observations, made with the unaided ear, that the sound was loudest at the back of the ball, gradually diminishing and almost vanishing at certain angles and again increasing to a feeble maximum in the plane perpendicular to the line of impact, convinced him that the air following the moving ball has its motion stopped suddenly so as to produce a compression wave which generates the sound. This problem he gave to his first student, the talented Sudhanshu Kumar Banerjee, who not only verified these qualitative observations but made very precise quantitative measurements and also worked out the complete theory. This also illustrates a trait in Raman — when he felt that he had basically understood a phenomenon his interest in pursuing it waned rapidly.

The whispering gallery

He noted a remark made by Lord Rayleigh in a footnote that his theory of the whispering gallery should be applicable not just to sound but to electromagnetic waves as well. Raman therefore initiated a series of studies (along with his student Bidhu Bhushan Ray) on the optical analogue of the whispering gallery, which gave results conflicting with some of Rayleigh's. Raman planned to verify the correctness (or otherwise) of these by experimenting in St. Paul's Cathedral when he went to Europe for the first time, the voyage that inspired him to start his researches on molecular scattering of light. In the experiments he did there (with GA Sutherland) Raman showed that the theoretical conclusion of Lord Rayleigh, that the sound waves travel in a comparatively narrow belt skirting the wall, was right, but two others, that the intensity in this belt decreases continuously as one proceeds radially inwards and does not fluctuate markedly as one proceeds circumferentially, were not in accordance with facts. Using a high-pitch source of sound and a sensitive flame detector they found pronounced oscillations as one proceeded inward radially (the overtones being heard clearly, while the fundamental was almost inaudible) — the distance between successive zones of silence being about half the wavelength of the source. There were also distinct periodic fluctuations while proceeding circumferentially parallel to the wall — completely in accord with the prediction made from the optical experiments.

On his return to India after his 6-week stay in England Raman energetically went round the country, experimenting in new whispering galleries, of which he discovered two in the newly built Victoria Memorial, one in the General Post Office in Calcutta and one in a granary at Bankipore (a curious paraboloid-shaped building, 96 ft high). This last one was intended for storing grain during famine but was never used.

Indian musical instruments

In the *soirées* held in his father's house in Vishakapatnam and in public concerts Raman heard South Indian music at its best — for those were the days of the great *vidwans* (maestros). He was particularly fascinated by the *mridanga* or the concert drum played with the hand and fingers by experienced drummers, using a highly developed technique. He marvelled at the manner of striking the drum head, and the regulation of the region of contact between hand and skin which elicited the requisite tone quality, intensity and duration of the sound.

His keen ear recognised that certain strokes appeared to bring out the first, second or even the third harmonic. Therefore he was somewhat surprised when he read in the *Theory of sound* that the natural vibrations of a circular stretched membrane (of uniform thickness) do not give rise to any harmonic sequence and so it is not simple to ascribe any particular pitch to them. Raman would not believe that the *mridanga* was in any sense musically defective as normal drums were. So he went on to demonstrate that the Indian musical drum produced as many as five harmonic overtones having the same relation of pitch to the fundamental tone as in a stringed instrument. He also showed that this was due to the central loading of the stretched membrane, and its behaviour presented a remarkable analogy to the law of vibrations of the homogeneous string.

The study by Raman of the string instruments, the *veena* and the *tanpura (tambura),* which are of undoubted antiquity, disclosed to him a remarkable appreciation of acoustical principles on the part of their ancient designers. Raman had noticed (probably when his wife played the veena) that the overtones did not die away as fast as the fundamental mode, but they seemed to steadily increase in volume. When he investigated the causes a surprise was in store for him. His simple experiments showed that the overtones having a node at the plucked point (a mode not permitted by the Young–Helmholtz law) sing out powerfully and that the position of plucking hardly appeared to make any difference in the intensity of overtones thus appearing to violate known acoustical principles. Raman traced this peculiar behaviour to the curved shape of the bridge in which the strings do not come clear off a sharp edge (as in European stringed instruments). The forces exerted by the string on the bridge near this grazing contact are in the nature of impulses occurring once in each vibration. These cause the retinue of overtones including even those absent initially in the vibration of the string. The woollen or silken thread traditionally slipped between the string and the bridge when adjusted properly enhances these effects making the sound very pleasing to the ear.

Bowed strings and the violin

During the decade 1908–1918 Raman investigated several aspects of the vibrations of stretched strings, culminating in his *Mechanical theory of vibrations of bowed strings of the violin family*, his *magnum opus* in acoustics. In the course of this work he developed ingenious techniques for exciting the vibrations and observing them. (This is all the more remarkable when one recalls that during most of this time he had no scientific position in a laboratory and had to perform his experiments after his regular duties in the Finance Department in which he was employed*.) In his studies on the wave motion of strings with discontinuous velocity distribution, Raman invented an amazingly simple way of producing an initial velocity distribution that varies linearly with distance from one end and suddenly drops to zero at the other end. He arranged the string to carry a weight at one end and made it execute a pendular swing about the other end. The string was suddenly brought to rest at the desired point by a suitably placed knife edge in its path. Using carbon arc lights, mirrors, tuning forks and photographic plates, he obtained curves that rival the oscillograph pictures of today.

Raman was clearly dissatisfied with the state of knowledge of bowed strings, let alone that of the violin. In the opening paragraphs of the monograph on bowed strings, he remarks:

> The present position of the subject cannot be considered satisfactory in view of the fact that no complete and detailed dynamical theory has been put forward which could predict and elucidate the many complicated phenomena that have already been found empirically by those who have worked in the field and that could also pave the way for further research. It was this defect in the present state of knowledge of the subject that induced me to undertake the investigations.

The starting point of Raman's mechanical theory of vibrations of bowed strings was the basic observation of Helmholtz that the bowed point of the string moves with

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* In one of his papers he thanks Dr Amrita Lal Sircar, the Hon. Secretary for the Indian Association for the Cultivation of Science, Calcutta, "for putting the resources of the laboratory of the Association and the services of the staff unreservedly at my disposal during hours at which few institutions, if any, would remain open for work".

the bow with a constant velocity up to a point and then releases itself from the bow and moves back with constant velocity until the bow catches it again and carries it with the same forward velocity as before. Thus the bowed point is forced to change its velocity discontinuously from one constant value (in the direction of the bow) to another in the opposite direction.

Raman set himself the task of establishing the correctness (or otherwise) of this description of the behaviour of the bowed string on the basis of kinematic considerations alone pursuing the argument, as he said, to its logical conclusions. He discarded from the beginning the normal mode analysis stating that it is unsuitable and adopted, instead, what would be called in current parlance the time-domain approach, although he merely called his method a graphical analysis. Considering the geometric requirements which waves travelling on a finite string fixed at its ends must satisfy, Raman arrived at the following two results: (a) "During one or more intervals in each period of vibration, the bowed point has a forward movement which is executed with constant velocity, equal to that of the bow, and (b) during the other interval or intervals the bowed point moves backwards, also with a constant velocity this being the same for all such intervals if there be more than one", thus confirming but also extending Helmholtz's observations to cover the case where there is more than one discontinuity in the velocity of the bowed point in one period. In his analysis Raman found a classification of the vibration patterns of bowed strings on the basis of the number of discontinuities in the velocity waves in the string.

After investigating the motion of the bowed string under more or less ideal conditions, Raman turned his attention to the effect of the bow pressure, bow velocity and bowing distance from the bridge upon the mode of vibration of the string and the resulting quality of the tone. From the point of the violin player these relations are extremely important. The player knows by his experience the limits of these parameters within which he can perform, but the physicist must establish these within a theoretical framework. Raman obtained limits for the minimum and maximum bowing pressures and considered the instabilities that can arise. He considered also the effects of the finite width of the bow, the yielding of the bridge and the coupling between the bridge and the string.

Seventy years after its publication, Raman's work is still relevant to the student of the acoustics of the violin and, for that matter, of other musical instruments too. Raman initiated studies in almost all fundamental problems in the physics of the violin, but unfortunately his work remained largely inaccessible to many readers. The physics of the violin is by no means completely understood even today.

The review in *Handbuch der Physik*

In 1926, when the first encyclopaedic work in physics, the *Handbuch der Physik,* was planned for publication by Springer-Verlag, Raman was asked to contribute an article on the *Musical instruments and their tones* (*Musikinstrumente und ihre Klange*). He was perhaps the only non-European scientist to be invited to write in this encyclopaedia. By this time the focus of Raman's scientific interests had shifted to light scattering. Unable to spare time from his researches in optics, he forced himself to write the article during the predawn hours. While our knowledge of musical instruments has advanced vastly in the sixty years since Raman wrote the article, it shows clearly how Raman perceived the significant problems involved in the analysis of the musical instruments.

The Raman–Nath theory

Raman's interest in acoustics waned in 1924. He wrote his *Handbuch* article reluctantly in 1926. Although Raman did not return to acoustics proper his attention did turn a decade later to a remarkable optical phenomenon occurring when a parallel beam of light is diffracted by ultrasonic waves. In modern electro-optic instrumentation the phenomenon of diffraction of light by ultrasonic waves is utilized in acousto-optic spectrometers which analyse the electrical signal to obtain its power spectrum. This volume includes for completeness a very well-known series of papers by Raman and Nath on this subject.

Conclusions

In reading these *Scientific Papers* it should be remembered that Raman's research predates the electronic era in acoustic measurements. Lee de Forest's triode valve and Wente's condenser microphone, which were both invented in 1917, were not yet commercially available for use in science laboratories. Even theoretical tools like the delta function and integral transforms which are routinely used today were not part of the repertoire of the physicist during that period. Raman's strength lay in his keen sense of observation, a highly trained and perceptive ear, penetrating insight into the physical behaviour of things combined with enormous powers of concentration. The reader would not fail to notice that

Raman does not frequently resort to diagrams to explain his reasoning but expects the reader to follow his arguments by exercising his imagination. Raman's style of writing is confident and stately, with a touch of aristocracy in it. He is never hurried, neither missing a word nor allowing an unnecessary one to slip in. The *mot juste* is always there. With Raman, style is the man himself, whatever Buffon might have meant by his aphorism.

Many acousticians of later years have wondered why Raman who was so successful in his work in acoustics had left it so suddenly. He stated that his monograph *On the mechanical theory of vibration of bowed strings* was the first instalment of more to come later, but none came. When Carleen Hutchins asked him (*ca* 1969) about this, he merely replied: "My studies on bowed string instruments represent my earliest activities as a man of science. They were mostly carried out between the years 1914 and 1918. My call to the professorship at the Calcutta University in July 1917 and the intensification of my interest in optics inevitably called a halt to further studies on the violin family of instruments." Raman, perhaps, never thought of himself as an acoustician; he was a physicist first and foremost and remained so to the last.

OPTICS

Introduction

The third volume of the *Scientific Papers* contains 65 papers covering many fields in optics which interested Raman: diffraction, theory and experiment; Huyghens' principle applied to a variety of phenomena including total internal reflection; the "radiant spectrum" and the speckle phenomenon; a variety of lovely optical interference effects; a heroic experiment to measure the so-called "convection of light" in moving air; a remarkable effect in conical refraction; the diffraction of light by ultrasonic waves; elegant experiments to establish the wavelike nature of periodic precipitates and the theory of the propagation of light in polycrystalline media.

This volume also contains the monograph entitled *Lectures on Physical Optics*, known more familiarly as the Baroda Lectures, since they were delivered in that city in 1941. This was originally planned in two volumes of which the first was ready for printing in 1943. Clearly other matters must have intervened, for the volume was published only in 1959 and the promised sequel never came. But even as an incomplete fragment, the Lectures deserve to be read for the masterly exposition of many interference and diffraction phenomena with a uniquely physical (and personal!) perspective. The book draws on forty years of living with light and is written in an inimitable style.

This introduction will have served its purpose if it guides the reader through the diverse aspects of optics in which Raman worked and whets his appetite for the original papers. His first paper was published in the *Philosophical Magazine* when he was eighteen. During his itinerant period, serving as a Finance Officer of the Government of India in Nagpur, Rangoon and Calcutta, it appears that his optical researches were sporadic as he was more interested in acoustics. But once he settled down at Calcutta, the floodgates opened. The summaries which follow are by no means exhaustive but may bring out some of the significant phases of Raman's optical researches spread over more than sixty years.

Diffraction

The obliquity factor

The first impression one gains from even the earliest papers is that Raman was completely familiar, right from the beginning, with the literature of the subject and kept a sharp look-out for new phenomena which would not fit in with existing concepts.

His very first paper, which was on asymmetric diffraction by an oblique aperture, led him to a direct study of the obliquity factor which had entered diffraction theory through the work of Kirchhoff. The geometry chosen by Raman led to a direct determination of this factor to which experiments in the usual geometry were rather insensitive.

The sphere and the disc

Because of its easy availability it was common practice to use a spherical ball instead of the circular disc to demonstrate the famous bright spot in the centre of a circular shadow (in Fresnel diffraction) and to assume that the sphere and the disc gave identical results. Raman and his brilliant student KS Krishnan suspected that this was not so because when the eye was placed at the central spot, it was noticed that in the case of the sphere the intensity of the boundary radiation was much less and the polarisation was also much less pronounced. This, together with the fact that the radiation can only emanate from a smaller circle, suggested that the creep of the wave over the surface must be taken into account. They made accurate measurements of the intensity of the central spot with a sphere and a disc of the same diameter. The spot inside the shadow of the sphere was much feebler than for

the disc at short distances, the two becoming identical at large distances. Using a simple geometric theory they could explain these observations.

The geometric theory of Fresnel diffraction

It is clear from reading these early optical papers that Raman was fully aware of the more rigorous electromagnetic treatment of the phenomena he studied but treasured the physical insight and heuristic power provided by Huyghens' principle, Fresnel's zones and Young's edgewaves. Raman felt that the rigorous procedures used to calculate Fresnel diffraction patterns afford no insight into the relationship between the forms of the obstacle (or aperture) and the character of the diffraction pattern.

He was greatly influenced by the discovery by Gouy in 1886 of the reality of Young's "edgewaves" — that a straight sharp metallic edge held in a pencil of light appears luminous and the strongly polarised light is diffracted through large angles. Raman used this concept of radiation from the boundary to explain his observation that for an elliptic aperture there is a concentration of luminosity on and within the evolute of the elliptic boundary in remarkable analogy to the caustics of geometrical optics.

Raman (and YV Kathavate) further noted that when the eye is moved away from the centre of the geometric shadow of the disc, the bright luminous circular boundary collapses to two bright narrow regions ("poles") on the boundary, at the ends of the diameter parallel to the line joining the eye to the centre. This was the beginning of the formulation of a geometric theory of Fresnel diffraction in which the intensity at any point in the shadow can be considered as arising due to the interference of the radiation from such poles. With the poles easily located geometrically, the delicate and yet intricate tracery of Fresnel patterns exhibited even by simple geometric shapes formed by straight edges (like the square, the rectangle or the triangle) could be deduced. Indeed, with similar simple rules, patterns for much more complex shapes with curved and straight edges could also be easily obtained.

The fascination for haloes and coronae

Raman was obsessed with the beauty of the coronae and haloes that appear around the sun and moon — an obsession that never left him. He studied the corona around the sun when he was in Nagpur in 1910, the lunar coronae in 1922 in Calcutta and the corona around Venus early in the morning just a year before he died. He took delight in producing and looking at them in the laboratory as these artificial coronae are more striking in colour than those seen in nature. It is also remarkable how much science Raman could get from his study and contemplation of this one phenomenon.

The discovery of the speckle phenomenon in 1919; the theory of X-ray diffraction of liquids propounded by him and Ramanathan in 1923; the derivation for the first time of the structure factor of atoms by considering X-rays to be scattered by a cloud of electrons and the subsequent classical derivation of the Compton effect formula (which led him on to the discovery of the Raman effect) all seem to have come out of this singleminded interest in coronae.

The radiant spectrum and the speckle phenomenon

In 1919 Raman discovered what is now called the speckle phenomenon. (Exener and de Haas also made the same discovery at about the same time tackling the same problem!) When a small source of light is viewed against a dark background one sees a "radiant spectrum" or coloured streamers appearing to diverge from the source. Raman deduced that this was essentially due to the diffraction corona formed by imperfections in the refractive medium of the eye — only that the interference effects due to the different particles must be superposed on to the diffraction effect. Because of this the maxima of the halo will exhibit violent fluctuations of intensity and appear "mottled". (These are the speckles one has become familiar with after lasers were invented.) When the light is white each mottle or speckle becomes a coloured streamer. Since the diffracting particles are randomly distributed, the intensity distribution of the mottles will be decided by the random walk process or the Rayleigh law. Many of these deductions were verified by Raman and his distinguished student GN Ramachandran in haloes formed by lycopodium powder on a glass plate. Raman conjectured that the "diffracting screen" in the eye may be a set of minute regions with small differences in refractive index with respect to the surrounding medium acting as a random phase grating, the Fourier transform of which gives the mottled image.

Wavelike character of periodic precipitates

Raman was intrigued by the formation of periodic precipitates in nature — the Liesegang phenomenon. He spent hours at the Indian Museum in Calcutta examining geological specimens manifesting this phenomenon, and

he also acquired many beautiful specimens from all over the world for his personal collection. The similarity between wave patterns and periodic precipitates had been noticed by many and the physical basis for this had been suggested as the Ostwald diffusion wave in three dimensions.

However, to Raman, such analogies would be without physical content unless the real distinguishing character of a true wave, i.e. the existence of a phase relationship, could be observed in the form of interference and diffraction effects.

An exploratory investigation (with K Subba Ramaiah) to ascertain the preferred orientation of the crystallites in such precipitates produced hundreds of magnificent microphotographs with thousands of Liesegang rings displaying what appeared to be inexplicable features. The main problem arises because while in a wavetrain the disturbance may be positive or negative, the density of the precipitate is necessarily a positive quantity. The first step was to recognise those features which could obviously reveal such effects unambiguously as effects due to waves. For example, a phase difference of half a wavelength must exist across a line of zero disturbance produced when two waves cross at an angle. This revealed itself by the staggering of the precipitates on either side of a line where no precipitation occurred. Gross and very fine structures of the precipitates seen under high magnification were identified as due to the recondite interplay of interference effects due to individual waves and groups of waves.

Conical refraction

Raman's first inroad into this subject was when he proved that the equipment usually available in physics laboratories (in those days) "to demonstrate internal conical refraction" actually demonstrated external conical refraction! This was followed by the discovery of a very remarkable optical phenomenon. A luminous object when observed through the singular direction of a parallel plate of aragonite forms a bright, well-defined, real, erect image of *unit magnification* with the unexpected property that the *image is continuous*, i.e. it may be observed anywhere along that line (and not at a single point as in the case of a lens). The light is also unpolarised. Raman showed that the image formation is due to the dimpled form of the wavefront and the intense concentration of luminosity which occurs on the singular point of the wave surface. Raman and his collaborators also made extended studies with naphthalene crystals (grown by the Bridgman method for Raman effect studies), in which the angles of internal and external conical refraction are ten times larger than in the traditional aragonite.

Einstein's aberration experiment

Two short papers in this volume reveal Raman in the role of a critic. In 1926, Einstein proposed an aberration experiment to distinguish between the quantum and (semi-) classical views of light. In the wave picture, a moving source emits a frequency which depends on direction due to the Doppler effect. The suggestion was that such a wavefront propagating in a dispersing medium like carbon disulphide would undergo an additional tilt proportional to the frequency gradient across it and hence give rise to a shifted image. In the quantum picture, Einstein believed that no such shift would take place.

Setting aside the behaviour in the quantum theory, Raman gave a brief and incisive analysis of the wave aspects and showed that no shift was to be expected in any case. He pointed out that Michelson's determination of the velocity of light with a rotating mirror effectively involved a moving source and drew attention to Gibbs' work in which the effect of a dispersing medium on the waves from such a source was analysed. The essential point was that one is dealing with a wave packet and the tilt of the wavefronts due to dispersion is inevitably accompanied by a drift through the envelope. The direction of the energy flow as defined by the wavefront at the centre of the group remains unchanged. As if this were not enough, Raman gives even more basic arguments starting from his favourite topic, Huyghens' principle, which lead to the same conclusion. From a modern point of view, one would say that the proposed experiment involves only second-order coherence and no difference between the statistical predictions of the quantum and semi-classical pictures is to be expected.

The Fresnel–Fizeau drag in gases

It may be worthwhile to draw attention to an interference experiment performed on an impressively large scale with air blown through two hundred-foot-long pipes in an attempt to measure the Fresnel–Fizeau drag for gases. The preparations for this experiment involved fairly large-scale civil works and equipment and the final expected effect was just a shift of one-tenth of a fringe. While the results were marginal, Raman's energy and enthusiasm as well as the confidence he must have inspired in those who supported him stand out. The experiment would probably be considered an ambitious one even today since efforts on a similar scale are under way all over the world to combine light from optical telescopes separated by large distances.

The Raman–Nath theory

Almost seven years after the discovery of the Raman effect, Raman turned his attention to a remarkable optical phenomenon occurring when a parallel beam of light is diffracted by ultrasonic waves. This volume includes, as did volume II on Acoustics, the very well-known series of papers by Raman and Nath on this subject. The original experiments in this field by Debye and Sears and by Lucas and Biquard showed a surprisingly large number of diffraction orders and an apparently irregular distribution of intensity among them, neither of which were satisfactorily explained by the ideas current at that time. The Raman–Nath papers introduced the physical concept of a corrugated (i.e. strongly phase-modulated) wavefront and the associated mathematical tool — a set of first-order differential-difference equations for the amplitudes of the various diffraction orders taking multiple scattering into account. Once these ideas were introduced the observations fell into place at one stroke. It may be worth remarking that the actual formula for the amplitudes involves Bessel functions in which Debye was an acknowledged expert!

Even more significant than the specific problem which gave rise to the theory were the ideas which found applications in other fields decades later. The multiple-beam dynamical theory of electron diffraction turns out (in retrospect) to be modelled on the Raman–Nath theory and it plays an important role in the interpretation of electron microscope images. The idea of an equation which is first order in the direction of propagation and second order in the transverse direction (the parabolic equation approximation) is contained in the Raman–Nath papers and now plays a significant role in the theory of wave propagation in a random medium. These applications involve going beyond the approximation of pure phase modulation and including the amplitude variations which this produces — a step which Raman and Nath had already taken in the later papers of the series.

Light in polycrystalline media

Raman's mineral collection contained a multitude of beautiful specimens like marble, alabaster, gypsum, feldspar, moonstones, labradorites, jades, opals, etc., which displayed striking optical effects. He felt that many of their properties were essentially due to fine crystallites of one phase imbedded (with or without preferred orientation) in an isotropic or birefringent medium. He wished to use his old technique of employing a beam of light as a probe to explore the secondary structure of these minerals and to understand their optical properties. His renewed interest in the beautiful Christiansen phenomenon and the propagation of light in polycrystalline media was because of this.

Raman was, of course, aware that to solve this problem one has to generalise the Raman–Nath theory for random phase gratings taking into account polarisation states. However, for practical reasons he contented himself with developing simple theories using which he could extract a considerable amount of useful information. The results of the experimental studies on these minerals are included in Volume IV of the *Scientific Papers.*

Total internal reflection and the mirage

A strong common theme underlying many of the papers in this volume is Huyghens' principle and the notion of secondary waves. For example, the phenomenon of evanescent waves occurring in the rarer medium in total internal reflection was given by a beautiful graphical interpretation in terms of a change in topology of the Fresnel zones. Raman backed this up by a detailed analytical calculation making contact with the usual theory. The value of this viewpoint is that it suggested further novel experiments involving diffraction by the evanescent waves both in the far field and in the near field. Errors and omissions in the literature on total reflection, by authors as distinguished as Kelvin and Schuster, were corrected politely but forcefully.

The interplay of geometrical optics and the wave theory is seen in many of Raman's papers but perhaps nowhere more clearly than in the paper on the optics of the mirage written in 1959 with his outstanding student Pancharatnam. This paper is noteworthy for the elegant way in which a stable layer of air with the desired refractive index gradient was produced and the beautiful pictures which the authors obtained with this arrangement. On the theoretical side, the authors comment on the conceptual difficulties of purely ray-optic treatment of the problem. A solution of the wave equation is given which accounts for the observed fringe pattern. (A similar solution had been given by workers in the field of ionospheric radiowave propagation some years earlier.) The associated wavefront is characterised (without a figure!) as made up of three sheets joined at cusps which travel along a caustic surface. Consequently, three images are to be expected in general and pictures showing their positions and parities are given. The principles elucidated by Raman and Pancharatnam for the terrestrial mirage were reintroduced many years later in the context of cosmic mirages. This

phrase refers to the formation of multiple images of faraway quasars formed by the gravitational bending of light by intervening masses. In efforts to model these so-called "gravitational lenses", the odd number of images, their parities, cusped wavefronts and caustics play a prominent role. The Raman–Pancharatnam paper should therefore be remembered not only for the wave-optical treatment of the mirage but also for the clarification of the associated geometrical-optics limit.

Conclusions

These optical papers of Raman are understandably less well known than his work on light scattering on the molecular scale. Nevertheless, they amply repay the attention of anyone interested in the subject even today. In addition, the papers give a fascinating picture of how their author approached the study of light which was certainly one of his lifetime preoccupations.

COLOURS IN NATURE AND THE DIAMOND

Introduction

Volume IV of the *Scientific Papers of C.V. Raman* contains 76 papers on a variety of topics. The first 21 are on a medley of subjects ranging from surface tension to zonal winds — subjects which interested Raman from time to time (from 1905 to 1968!). The second set of 39 papers deals mainly with the colour displayed by objects in nature, mostly minerals, whose visual beauty had a strange fascination for Raman. The last set of 16 papers are again on a mineral for which Raman had a special affection — *diamond*. As in the introductory essays for the previous volumes, I shall comment on some of the topics touching on historical details where appropriate.

Miscellaneous papers

Surface tension: The experimental work reported in the first paper of this volume was started sometime in 1905. It is a neat piece of research, executing a casual suggestion made by Kelvin in his *Popular Lectures and Addresses* that the surface tension of a liquid can be determined by measuring the curvature of a suspended drop. The young Raman displayed skill and ingenuity in rigging up a spark generator to illuminate the suspended drop to take instantaneous photographs of its shadow, correct for any errors that diffraction of light may introduce, etc.

Viscosity: Raman's phenomenological theory of viscosity is based on the hypothesis that the liquid state is composite in character consisting in part of molecules rigidly attached to each other (as in a solid) and in part of molecules which are relatively mobile (as in the gaseous state). Taking the energies required to separate a pair of molecules of each type and applying the Boltzmann distribution law, Raman derived a simple formula connecting the viscosity of a liquid with that of its vapour. From this he computed the viscosity of liquid benzene at different temperatures. The calculated values agreed with the experimental ones to within 2 parts in a thousand! Staudinger, the pioneer in polymer chemistry, later found Raman's model eminently suitable to correlate the viscosity of solutions of molecules in various states of polymerization.

Impact: Raman's interest in struck strings led him to investigate the problem of impact where he made some significant advances both in theory and experiment. While using Hertz's theory, Raman considered all the possible modes of dissipation of energy which could affect the coefficient of restitution when two spheres collide. These were (a) the sound waves and (b) the stresses occurring during impact when they exceed the limits of perfect elastic recovery. His group had shown that the sound waves were generated by the impulses communicated to the atmosphere due to the sudden reversal of the motion of the spheres and the energy thus dissipated was negligible; the dissipation due to imperfect elasticity would also be negligible when the velocities of impact were very small. Therefore, Raman argued, the coefficient of restitution at extremely low velocities must tend to unity irrespective of the nature of the material of the balls or their elastic properties. This result was verified by a series of beautiful experiments on balls made of different materials with a wide range of elastic and other properties. Raman also used the idea that part of the translational energy is transformed into elastic wave motion in the substance of the solid to calculate the coefficient of restitution in the case of a sphere and a flat plate. Assuming annular flexural waves to be set up in the plate, the coefficient of restitution was calculated and found to agree well with the experiment.

Many concepts of the manner and mechanism by which a solid breaks down under impact came out of these early researches. When a sphere impacts a plate the stresses in the centre are compressive and the fracture does not start there. The fracture is initiated as a circular crack near the margin and it travels inwards into the plate obliquely at 45° along the surface of maximum shearing stress set up during impact. Raman was also amongst the earliest to use interferometric methods to study the nature of the deformation after breakdown.

The plumage of birds

Colour, the striking feature of the plumage of birds, which fascinated Raman no end, was the subject of many of his studies. The interest was all the more as the optical characters and distribution of colours were so different in different parts of the same bird, in different specimens and in different species that no single explanation would suffice. Every phenomenon known to the optical scientist — interference, diffraction and scattering of light — and more had to be invoked. Interference due to thin films on the surface, selective spectral reflection from stratified films, the diffraction of light by discontinuities not small compared to the wavelength of light, the Tyndall effect due to minute air cavities, the anisotropic scattering due to elongated holes and particles, all contribute to these colours. Further the delicate interplay of these physical effects with the chemical colours enhances the spectacular chromatic display seen in birds.

Raman published only one paper on this subject but gave dozens of lectures to large audiences. His favourite title was "Birds, Beetles and Butterflies" but each lecture was unique and usually contained an account of a study he had made of a specific object from his remarkable collection. He was particularly fond of the iridescence displayed by the magnificent tail feathers of the peacock and the gorgeous plumage that covers the head and neck of the Himalayan pheasant. The ubiquitous kingfisher and the plebeian parrot were also subjects of his study. Those were days when colour slides were not yet in vogue. For his lectures he did use well-mounted museum specimens. At one of these lectures on the common or garden Indian jay Raman painted word-pictures of this bird and its colourful feathers so graphically that the listener could see in his mind's eye the succession of coloured bands of alternating deep indigo-blue and light greenish-blue, changing dramatically when the bird was in flight; dull and drab when the light is from behind and turning to a brilliant green with almost enamel lustre when lit from the front. The feathers display transient colours after a shower when damp — the blue indigo becoming shimmering green or a dark blue or even a dramatic deep violet depending on the position of the sun and the observer. To Raman birds were beautiful and hence fit subjects for serious study.

Colours of minerals

In the new Institute he built for himself to work in peace after he formally retired, he started by arranging his magnificent, now famous, collection of minerals, specimens he had gathered from all over the world for the extraordinary optical phenomena they exhibited — limestones, marbles, alabaster, gypsums, tourmalines, agates, quartzites, jades, amethysts, fluorites, micas and serpentines, iolites, malachites, lapis lazuli and feldspars.

Feldspars were truly intriguing — labradorite, a special variety, displayed brilliant colours; another group, moonstones, found use in jewellery because of their beautiful optical effect called *schiller*. He continually leaned on his old experiences with scattering of light in liquids. For example he compared the blue *schiller* from the best moonstones he had with the blue opalescence in binary liquid mixtures as the critical temperature is approached; or the spectacular blue colour exhibited by many labradorites with the blue opalescence when water is added to methanol containing benzene in solution (when benzene tends to separate). He concluded that although in a common macroscopic sense these substances — moonstones and labradorites — were monocrystals, they had optical heterogeneities in them.

To begin with, the basic facilities had not yet been established at his Institute. There was as yet no electric power and so he had to revert to the use of his old trusted technique of using a beam of sunlight (the technique he had used to discover the Raman effect) to explore and understand the optics of these substances. He felt that the passage of light through the mineral and its diffusion would reveal the existence and nature of optical heterogeneities, the local variations in composition and of refractive index. These optical inhomogeneities could be embedded in a matrix. But there were a large number of possibilities. The inhomogeneities could be cavities or crystallites or just variations of composition. They could be isotropic or birefringent, oriented randomly or with a preferred direction; they could show periodicities in one, two or three dimensions. The medium itself could be amorphous or crystalline, polycrystalline or a monocrystal, isotropic or birefringent. All these variations Raman wanted to probe with just a beam of light. He knew that it would be best to generalise the Raman–Nath theory

considering not only the phase corrugations due to these random optical inhomogeneities but also the states of polarisation. But being pragmatic Raman (and Viswanathan) developed a theory based on simpler models. The character of the diffused light, its spectral nature, its intensity and state of polarisation, and its distribution in different directions and variation with the setting of the crystal and the direction of the passage of light furnished him with the data needed to infer the nature and distribution of the local heterogeneities.

He studied a variety of minerals, iridescent potassium chlorate, iridescent shells, feldspars, moonstones, fiery opals, iridescent agates, iridescent calcite, iridescent quartz, jadeite, cryptocrystalline quartz, polycrystalline gypsum (and also a variety of natural and synthetic fibres). It is remarkable how much detailed information he could extract from this simple means of sending a beam of sunlight through the mineral. Many of his conclusions were right, but some were wrong. For example, Raman (and Jayaraman) deduced that in opal the fiery colour was due to isotropic inhomogeneities with a refractive index lower than that of the surrounding medium but segregated periodically. Later electron microscopic studies showed that they were isotropic and of lower refractive index and also periodically distributed in the lattice but were really submicroscopic air bubbles!

He was amongst the earliest to worry about the existence of periodic compositional segregation in minerals which he felt was much more common than usually supposed. This phenomenon underlies the modulated structures which are widely studied today.

Pearls

A special word about the pearl: the gemstone which does not need the services of a lapidary to enhance its natural beauty. The precise understanding of the optics behind its loveliness was a matter of more than ordinary interest to Raman. He (and D Krishnamurti) discovered that light falling normally on the rear surface does not travel through the pearl but around it (as does sound in a whispering gallery — a subject in which he had done much research), following the lamination of its structure. The beauty of the pearl is to be found in this effect, together with the superposition of the chromatic diffusion halo and also the reflected light.

Diamond

Soon after the discovery of the Raman effect, C Ramaswamy, Raman's younger brother, asked him to suggest a research problem which he could pursue. Seeing the diamond ring that the newly wed Ramaswamy sported on his finger, Raman suggested the study of *modified scattering* in diamond. Ramaswamy discovered the famous 1332 cm^{-1} Raman line of diamond. This was followed by the work of Bhagavantam, one of Raman's star pupils, recording the Raman spectrum of a 140-carat diamond that was borrowed from the Maharaja of Dharbhanga. Bhagavantam graphically describes how he spent two days and two nights in the dark spectroscopy room in trepidation praying that nothing untoward should happen to the precious gem. He confirmed Ramaswamy's discovery and also recorded the complex luminescence spectrum around 4152 Å. Raman must have had this in mind when he related how he was "reduced to the expedient of borrowing diamond rings from wealthy friends who, though willing to oblige, were slightly apprehensive about the fate of their property". Raman later visited another of his wealthy friends when he was "graciously permitted by His Highness the Maharaja of Panna to examine his famous garland of fifty-two large (Panna) diamonds of exquisite beauty, all in their natural uncut state as crystals ranging from 25 carats to 2 carats strung into the form of an exquisite necklace". He then wrote: "With their perfect geometric forms and their smooth lustrous beauty they look absolutely fresh from nature's crucible, although actually taken from sedimentary formations a thousand million years old. The strongly marked curvature of the crystal faces and the smoothly rounded edges are a surprising feature of these crystals." These diamonds as seen now, according to Raman, are exactly in the same state as they were when first formed. The love affair with diamond had begun.

Obtaining the material in the form suitable for study was his first obstacle. He discovered that flat pieces of diamond of excellent quality, not too expensive, could be purchased in useful sizes from many jewellers in India. The diamond auctioneers in remote corners of India were very accommodating. They had never seen such a colourful personality, that too a scientist, sitting crosslegged in their midst. Contrary to all their usual custom, they obligingly permitted him to examine each specimen under a microscope, a fluoroscope and a strain viewer (which he carried with him) and permitted him to form his own "lots" wondering why anyone should mix such expensive stones with such utterly worthless ones! Raman purchased hundreds of representative specimens, euhedral crystals, cut gems, or plates. They were bought for the beauty of their form, colour, fluorescence or birefringence.

The results of the X-ray analysis of the crystal structure of diamond by W H Bragg and W L Bragg (1913) have been regarded as demonstrating that diamond possesses the highest holohedral cubic symmetry. This was in conflict with the view of all the earlier crystallographers. Raman had in his personal library the works of some of the recognised authorities on mineralogy from all over the world — Groth, Liebisch, Hintze, Dana, Lewis, Miers, etc. It was his custom to read these regularly, particularly those with painted illustrations. Without exception diamond was assigned to the ditessaral polar class, i.e. the hemihedral tetrahedral class of the cubic system. The assignment was based on the fact that although crystals of diamond exhibiting octahedral symmetry of form were seen in numbers, specimens showing only the tetrahedral symmetry were also forthcoming. It was the view of these crystallographers that the highest symmetry when observed was the result of supplementary twinning of positive and negative tetrahedral forms. The manifestation of grooves in many octahedral crystals was a clear proof of this. Raman was, of course, familiar with Van der Veen's result that diamond does not exhibit any pyroelectric properties, which was considered irreconcilable with the assignment of tetrahedral symmetry.

Much controversy had taken place over the question of whether diamond is actually octahedral or tetrahedral. Raman was very troubled by all this. In the twenties when he represented India at the bicentenary celebrations of the Academy of Sciences of the U.S.S.R. he discussed this with many Russian crystallographers and with Sir Henry Miers, the reputed British mineralogist, who represented the United Kingdom and the Royal Society at these celebrations. Miers reiterated the statement he had made in his book, "The problem is now regarded as decided in favour of the tetrahedrite class." Raman paid much credence to the conclusions of the older scholars and felt that the evidence they had gathered after careful study must not be so easily brushed aside. He also believed that while the structure as determined by X-rays was essentially right, the symmetry itself was open to question because of the basic ambiguity of X-ray methods in symmetry determination.

In 1934 many things happened. Nagendra Nath at Raman's instance studied the dynamics of the diamond lattice and published a series of papers in which he showed that the fundamental frequency of the diamond structure (1332 cm^{-1} frequency) is a triply degenerate oscillation of the two face–centred cubic lattices of carbon atoms with respect to each other. In the same year the celebrated article of G Placzek, "Rayleigh–Streuung und Raman Effekt", appeared. In this Placzek discussed the relation between the symmetry class of crystals and their activity in infra-red absorption and the Raman effect. He showed that for groups which contain a centre of symmetry the selection rules for the two are complementary; but for groups that do not have a centre of symmetry there is a possibility that the same vibration may appear both in Raman effect and in infra-red absorption. In the case of the triply degenerate vibration in a crystal having octahedral symmetry it can manifest itself *only* in the infra-red absorption *or* in scattering of light but *not in both.* On the other hand in a crystal with tetrahedral symmetry such a vibration must appear *both* in infra-red absorption and Raman effect or *can appear in neither.*

Also in 1934, Robertson, Fox and Martin showed that diamonds are not identical in their behaviour in infra-red absorption — one group which represents the majority of cases showing strong absorption in the 1300 – 1350 cm^{-1} region which is wholly absent in a second and rarer variety.

When his collection of diamonds had expanded Raman decided to examine (along with a student) a large number of diamonds in their natural form, obtained from various sources, many of them from India. There was no doubt whatsoever that many of these exquisite, clear, water-white crystals displayed the symmetry of the tetrahedral class. To Raman it appeared that the view of the earlier crystallographers in assigning the hemihedral or lower symmetry to diamond was justified and it was vindicated by the infra-red absorption data and the selection rules so far as the common variety of diamond was concerned. He was also certain that the rarer variety *must* be credited with the full holohedral symmetry. Here was the enigma. It was quite confusing.

Raman was convinced that the intensive study of diamond itself would surely not only provide the answer but could be of importance to physics and chemistry. He felt history had a way of repeating itself. For did diamond not exhibit in a striking fashion many phenomena which are scarcely noticeable in other solids under ordinary circumstances? The variation of specific heat with temperature was known as an experimental fact in the case of diamond at least 50 years before it was recognised as a universal property of the solid state. Weber's data published in 1875 formed the basis of Einstein's epoch-making paper introducing the quantum theory of specific heat.

So experimental activity was mounted at a rate never

before undertaken in India and results and techniques began to pour out.

Even if it is conceded that diamond has tetrahedral symmetry, the two variant subclasses, the positive and negative tetrahedral structures, would be identical in respect of energy of formation. It is therefore possible to have both of these in the same structure but this cannot give a crystal which has a centre of symmetry at microscopic level.

To explain the existence of diamond with octahedral symmetry Raman was obliged to give symmetry properties to the atom itself — that the carbon atom *itself* had a tetrahedral symmetry (as distinct from the symmetry of its bonds). If the structure had either positive tetrahedral carbon atoms or negative ones *only* and they were all oriented in the same direction, a diamond structure with positive or negative tetrahedral symmetry would result giving two tetrahedral forms of diamond. A positive tetrahedral carbon atom could combine with a negative one in two ways to give a centre of symmetry between the two atoms; and with their apices pointing to each other or away from each other, giving two more forms of octahedral diamond structure. He then considered the effect of these four types intermingling in the same crystal, the strains they would generate, their imperfections as seen in X-ray topography, their infra-red absorption, the fluorescence they would exhibit under ultraviolet light and X-rays, the ultraviolet absorption and many other properties. He tested these in his diamond plates — and the correlations were striking. He could look at the birefringence patterns of a plate and predict the patterns they would show in regard to other properties. It was almost uncanny. Raman therefore thought he was right. It is now known that all this was based on a wrong premise and the accepted explanation of these variations is that they are caused by impurities. The possible role of impurities had in fact been suggested to Raman but it went against his intuition and he rejected it.

It is interesting how intuition played a vital role in his earlier important discoveries. The discovery of the Raman effect owed much to his intuitive belief, dating from 1923, that the "weak fluorescence" that he and his students observed in light scattering was not due to impurities but originated from the molecules that constituted the liquid. It must have been this unshakeable conviction that made him drive his student collaborators into purifying and repurifying scores of liquids to look for specific characteristics in the scattered light, which would distinguish molecular scattering from fluorescence due to impurities. However the same intuition seems to have played him false in the case of diamond. Unable to purify his diamonds, he studied hundreds of specimens. All the while he was unwilling to believe that his "prince of crystalline solids" could be flawed by major impurities. Years later it was established that many of the phenomena he and his students discovered arose due to impurities (like nitrogen) in the diamond lattice. It is ironic that the symmetry changes induced by these are similar to those Raman proposed to explain the observed phenomena and which he considered intrinsic to the carbon atom.

We have pointed out that Raman's vision of intrinsic tetrahedral symmetry in diamond did not prove correct. But the number of new ideas and techniques which came out of the extensive studies of this crystal is truly remarkable. The use of X-ray topography for the study of crystal imperfection was discovered independently in Raman's laboratory. The application of the Jamin effect (now called ellipsometry) for the study of thin surface films was introduced. The cleavage properties and energies and hardness anisotropy of crystal surfaces were studied and ideas such as dangling bonds discussed. The fluorescence and phosphorescence of crystals were studied and a whole range of optical effects such as second-order Raman scattering, Brillouin scattering, photoelastic properties of solids, and many others were systematically investigated, many for the first time. It would be no exaggeration to state that a whole school of crystal physics grew and flourished in that period with its roots in Raman's fascination for diamond. Even though the tetrahedral symmetry that Raman sought proved elusive, the tools and results of his quest came to be of lasting value to the study of the physics of solids.

CRYSTAL DYNAMICS

Introduction

Volume V of the *Scientific Papers* represents the work done by C.V. Raman mainly on various aspects of crystal dynamics. The first set of papers relates to the experimental discovery of thermal diffuse X-ray reflections as also temperature-independent diffuse reflections. Raman thought the latter were due to the interaction of X-rays with optical phonons and there was much dispute about this interpretation. The next set of papers are on his theory of the dynamics of crystal lattices which was also the subject of a raging controversy. He then published a large number of papers using his crystal dynamics to calculate the vibrational spectra and the specific heats of crystals. These papers are also included in this volume, as also the four papers in which he and KS Viswanathan developed a generalised theory of elasticity.

Raman's quest for the interaction between optical phonons and matter ended in 1928 but by then he was already looking further. In the lecture "A new radiation"(1928) he said: "If a quantum of radiation can be absorbed in part and scattered in part in the optical region of the spectrum, should not a similar phenomenon occur in X-ray scattering? The type of scattering discovered by Professor Compton may possibly be one of the numerous types of scattering with modified frequencies; some with a line spectrum and some in the nature of continuous radiation."

His foresight was borne out a decade later when he investigated the interaction of X-rays with crystal vibrations. It was known that the possible vibrations in a crystal fall into two broad types. The acoustic spectrum was made up of elastic waves which traverse the crystal in all directions ranging in frequency from zero to a certain upper limiting value as postulated in Debye's very successful theory of specific heats at low temperatures. The second type consisted of "optical" vibrations of the crystal which could also give rise to well-defined spectral lines in infra-red absorption or in the Raman effect.

Diffuse X-ray reflections

The effect of thermal vibrations on the intensity of X-ray reflections had been considered by many scientists as it was of immediate significance in the determination of crystal structures by X-ray methods. When X-rays fall on an atom occupying a fixed position in a crystal it would emit in all directions secondary radiations having the same frequency as the primary X-rays falling upon it. In a crystal these secondary radiations cancel in most directions except specific discrete cases in which they reinforce to give sharp (Laue–Bragg) "reflections". An oscillation of the atom about its position of equilibrium would result in a periodic variation of the phase of the secondary radiation and according to Max von Laue's analysis in 1926 the secondary radiation itself would have components with frequencies increased and diminished respectively by the oscillation frequency of the atom. As pointed out by Debye and Waller the effect of these vibrations is to decrease the intensity of the X-ray reflections.

Raman pictured these vibrations as periodic pulsations of the electron density equivalent to superposing a dynamic stratification on each static stratification. The phase of oscillation of the atoms varies from one unit cell to the next. A progressive change in the phase of the atomic pulsation in a direction parallel to the particular set of planes is then equivalent to a tilt of the wave-front of the dynamic pulsations away from the static crystal planes. The Bragg condition for the particular spacing (of the periodic pulsation) must be satisfied so that one can get a reflection from the tilted dynamic sets of planes. One notices that this new type of reflection is in a direction which is displaced from the usual geometric position.

Raman had thus shown that X-ray reflections from the static and dynamic planes are separable by the simple

device of tilting the crystal away from the correct glancing angle for the X-ray wavelength employed (a procedure now called exploring the reciprocal space). There should therefore be a measurable intensity of X-rays diffracted in a direction other than the Bragg maximum.

Raman and Nilakantan looked for the existence of such dynamic reflections and observed them in various crystals. In diamond they observed two types of diffuse reflections — one temperature-dependent and the other temperature-independent. These "reflections" from the dynamical periodicity induced by thermal and other waves in the crystal structure are by their nature diffuse, i.e. less sharp than the conventional Bragg reflections. The discovery of the non-Bragg reflection probably made for the first time in Raman's laboratory in 1939 was confirmed by the work of several other laboratories.

Raman derived the correct formulae for the directions of these non-lattice reflections. In working out the theory of the dynamical reflections, Raman emphasised the change of frequency occurring when X-rays interact with the thermal waves stating that if the X-ray reflections could be analysed by a spectroscope of sufficiently high resolving power, one would find components with frequency greater and less than that of the X-rays by an amount equal to the frequency of the waves in the crystal. At that time, the diffraction of neutrons had not yet been demonstrated and he was probably one of the few to emphasise the change of frequency and the change of direction of scattering. In fact, it is just the combination of these two measurements that gave the diffraction of slow neutrons by lattice vibrations and other excitations the fundamental role it now enjoys in exploring condensed matter. Raman's formula showed that in the case of acoustical waves regular geometric reflections would clearly be visible only for small tilts away from the Bragg angle. However the temperature-independent reflections from diamond were sharper and were persistent over much larger angles. Raman and Nilakantan attributed them to the excitation of optical vibrations of the crystal lattice by the X-ray photon and termed the phenomenon "quantum reflection". Strangely enough Raman was well aware that impurities in crystals under certain circumstances can also give rise to such reflections. Unfortunately, he had intuitively ruled out the possibility of any impurities in diamond. Because of this he was drawn into a long controversy with the distinguished crystallographer Kathleen Lonsdale about these diffuse reflections from diamond which she believed were due to imperfections of various kinds. Years later it was established without doubt that nitrogen and other atoms are present in diamond as substitutional impurities. The extra diffuse spots that Raman and Nilakantan observed were in fact associated with platelets of nitrogen impurity!

It is strange that the discovery of the Raman effect was due to his intuitive belief that the weak fluorescence which his group observed in light scattering was not due to impurities. But the same intuition seems to have played him false in the case of diamond when he was older by twenty years.

Interest in crystal dynamics

In 1939, using the Raman effect, Raman and Nedungadi discovered what is now called the "soft mode process" for crystal transformation. In the same year he and Nilakantan also discovered two types of diffuse scattering, one of which he thought was due to the excitation of an optical phonon. These two discoveries made him look for better experimental methods of determining the vibrational spectra of crystals. He was also interested in formulating methods of enumerating these vibrations and computing their frequencies, at least in the case of simple crystal structures like rock-salt, diamond, etc. It was at this stage that he returned to the remarkable photograph of the Raman spectrum of NaCl published by Fermi and Rasetti in 1931. They illuminated a 5-cm-thick NaCl crystal with the 2536·5 Å resonant radiation from a magnet-controlled water-cooled quartz mercury arc. To prevent the complete fogging of the photographic plate which would have resulted from long exposures with intense illumination, Rasetti had introduced a filter of mercury vapour which absorbed the resonance radiation producing a clear photograph in which spectral lines could have been seen as close as fifty wavenumbers from the incident line. The actual spectrum recorded was the second-order Raman spectrum of NaCl (the first order being forbidden by symmetry). It was described by them as follows: "The effect is however very different from the usual Raman effect observed in crystals. It consists of a continuous spectrum over which were superposed a few apparently randomly distributed maxima and minima." Raman discerned in these "randomly distributed maxima and minima" nine "lines" which was exactly the number of vibrations of the NaCl lattice expected on the basis of his theory.

So impressed was Raman with the Rasetti technique that he urged his associates to set up this arrangement immediately in his laboratory and if possible improve upon it by using higher dispersion spectrographs. The second-

order Raman spectra of NaCl and diamond were recorded by RS Krishnan and in his skilful hands it became perhaps the best method for studying the vibration spectra of crystals till it was overshadowed by the use of lasers.

Reformulation of crystal dynamics and its achievements

Raman formulated his crystal dynamics starting from the classic work of Lord Rayleigh. In a normal mode of a connected system of particles, they all vibrate with the same frequency and can have either the same or opposite phases. Raman then introduced the basic principle of crystal architecture: that the crystal consists of sets of equivalent atoms ordered in such a manner that each atom in a set is both geometrically and physically related to its environment in exactly the same way as every other atom of the same set. He deduced that in a normal mode of a crystal, equivalent atoms in it all have the same amplitude of vibrations, their phases being either the same or opposite in successive cells of the lattice along each of the three axes. This is equivalent to saying that atomic vibrations repeat themselves exactly in a space pattern of which the unit has twice the dimensions in each direction and therefore eight times the volume of a unit cell of the crystal lattice. If, therefore, each unit cell contains p atoms then these cells contain $8p$ atoms and these have $24p$ modes of vibration or $(24p–3)$ normal modes if one excludes the three translations. Hence according to Raman the fundamental result emerges that a crystal containing p interpenetrating (Bravais) lattices of atoms has only $(24p–3)$ characteristic modes of vibration each of which is characterised by a specific frequency. In $3p–3$ of these modes equivalent atoms have the same phases of oscillation in adjacent cells and in the $21p$ other modes the amplitudes are the same while the phases alternate in adjacent cells (along one, two or three axes of the lattice).

Raman next proceeded to give a physical picture of the $21p$ modes in cubic crystals. For example, in the case of rock-salt these modes are oscillations of the alternate planes of equivalent atoms in a crystal relative to each other, the planes being either the octahedral planes or the cubic planes. The degeneracies were then calculated and the modes enumerated to be nine for NaCl, eleven for CsCl, eight for diamond, etc. The description of each mode was given. The number almost in every case corresponded to the number of the peaks observed in the second-order Raman spectra of these crystals. He then proceeded to calculate the frequencies of these $24p–3$ modes for many crystals in terms of force constants. The agreement between calculated frequencies and the experimentally observed ones was very good. He then calculated the specific heats of these crystals assuming the frequency spectrum to consist of $(24p–3)$ discrete frequencies and using them as simple Einstein oscillators, with an appropriate Debye term added. Again the agreement between theory and experiment was rather good.

The large number of papers on the Raman spectra and infra-red spectra of a number of crystals had valuable experimental data and good fits with theory and one would have thought that all these indicated a success of his ideas. Indeed, if these papers had been presented as a simple and physical approximation capturing the essential features of optical modes, they would have been regarded as a significant contribution in the field. But to Raman, the successes of his approach meant that the entire body of lattice dynamics as formulated by Born and von Karman and developed by Born and his students was completely wrong. He launched a scathing criticism of their ideas on fundamental grounds. This period was marked by bitter controversy, basic errors, and much wasted time and efforts on his part and can only be described as a tragic failure.

The lattice dynamics controversy

Raman deduced that a crystal having N cells (with p particles in each cell) has only $(24p-3)$ modes. His critics pointed out that this is in direct conflict with Lagrange's theorem, which states that a dynamical system composed of Np particles has $3Np–3$ normal modes. Since N is large for real crystals, theory predicts that the phonon spectrum must be continuous, in conflict with Raman's assertion that it is discrete; and further $(24p–3)$ is a very small number compared to the actual number of degrees of freedom of a crystal. Of course, it should be mentioned that in fitting the specific heats of solids, Raman used the correct total number of degrees of freedom, which means that he regarded his modes as highly degenerate.

Raman's perceptive student KS Viswanathan, starting from the conventional lattice dynamics, proved that the group velocities of the lattice waves vanish for these special modes, which correspond to the limiting (zone centre or zone boundary) optical modes. Since the density of states in the frequency spectrum is inversely proportional to the group velocity of the waves, these (Raman) modes correspond to singularities which are particular cases of those classified in general by Van Hove a few years later. From the conventional lattice dynamics it can be shown that these frequencies should appear as

maxima in the Raman spectra of crystals and in this way the theory is consistent with Raman's observations. It was pointed out correctly that even if the group velocity vanishes for this handful of $(24p-3)$ modes, it does not mean that the other modes do not exist, nor does it mean that the frequency spectrum is discrete.

Raman rejected the notion used by Born and von Karman that normal modes could be described in terms of travelling waves. To him the Born cyclic postulate was an artificial device without any physical meaning. This particular criticism of Raman seemed a valid one and therefore many theoretical physicists looked into it. For example, Peierls proved that the normal modes in a crystal with boundaries are by no means identical to those of a cyclic crystal (with no boundaries) but the frequency spectra of the two are practically identical if the ratio of the number of atoms on the surface to those in the bulk is small. Thus except in special situations where surface effects are likely to be important the mathematically simpler (though artificial) picture given by the cyclic postulate is a very good approximation. It is of some interest that Peierls published this paper in an Indian journal.

Since Raman started from the correct definition of the normal mode given by Rayleigh, at what stage did the theory take a wrong turn? It is in his second assertion that in a normal mode in a crystal, equivalent atoms in adjacent cells must vibrate with the same amplitude in the same or opposite phases. This is reminiscent of the famous Bloch condition in solid state physics, which is only valid for travelling waves! Raman inappropriately imposed this condition on a standing-wave situation, which completely restricted his attention to 8 cells. Although this proved important in explaining and calculating the frequencies at the "zone centres" and "zone boundaries" and explained some important features observed in the second-order Raman spectra of crystals, the nature of the complete lattice spectrum was missed.

This volume also contains papers on a new view of the theory of elasticity in which the symmetries of the stress and strain tensors and the number of independent elastic constants differed from the standard view. These papers naturally proved controversial as well.

The controversies in perspective

This volume contains many papers based on ideas which were hotly disputed even in Raman's time and are recognised to be incorrect today. It is probably natural that a scientist who relies on his powerful intuition (as Raman did) would sometimes be led into errors. The experimental proof of the spin of the photon has already been mentioned in Volume I and the intrinsic tetrahedral symmetry of diamond in Volume IV. In this volume, we have his view that the excitation of optical phonons was the cause of the temperature-independent diffuse X-ray reflection in diamond. In all these cases, it is fair to say that the state of knowledge at that time left genuine room for doubt. It is true that in his later years Raman was prone to ignore or dismiss evidence which contradicted his point of view.

His work on the foundations of lattice dynamics stands apart from the three instances given so far. Firstly, it concerned a subject in which he was an acknowledged master—waves and vibrations. One sees a combination of many factors which shaped his strong, unyielding and ultimately incorrect objections to Born's theory of lattice dynamics. To start with, the artificial-looking cyclic postulate must have put Raman off. Elaborate calculations (not fully carried out till the advent of computers a decade or more later) were needed to predict the simplest of optical and thermal properties from the Born theory. Lacking the notion of singularities in the spectrum, again not to come for a decade, the sharp features seen in the Raman scattering found no explanation. In this situation it is natural that Raman sought an alternative and once it turned out to match the experiments, he was blind to its theoretical flaws. By the time the crucial evidence in favour of the Born theory had accumulated, his attitude had hardened and even his close associates and students could not get through to him on this subject. More than any of the other errors mentioned earlier, it was his stand on lattice dynamics which genuinely diminished his stature as a scientist in later years. While this controversy (and others to a lesser extent) caused a great deal of pain to those around him at that time, they fit into a pattern which is not at all unusual in the history of science. The same qualities (intuition and persistence in Raman's case) which are responsible for a scientist's great successes can also let him down on other occasions. It is essential for the biographer, historian or even the student of science to be well aware of this side of Raman and hence these papers have been reprinted here in full to give a complete picture of the man. But in the long run, there is no doubt that Raman's towering contributions to so many areas of physics — exemplified by the other volumes of his collected papers — will outweigh by far the errors of interpretation and judgement we have just discussed.

COLOURS AND THEIR PERCEPTION

Introduction

Volume VI of the *Scientific Papers* contains the work C.V. Raman did in the last decade of his life. It also contains the monograph he wrote, entitled *The physiology of vision*.

As the previous volumes of these collected papers show, his major research interests continually changed over the years — acoustics (1910–1920), optics and scattering of light (1920–1930), ultrasonic diffraction and the application of Brillouin scattering to liquids and Raman scattering to crystals (1930–1940), diamond and vibrations of crystal lattices (1940–1950) and optics of minerals (1950–1960). Clearly a change seemed due in the early sixties and it came with his renewed interest in vision.

The process by which light is perceived by the human eye must have always intrigued Raman. It was the visual impact of the blue of the Mediterranean which provoked his entry into the field of molecular scattering with such success. Yet he knew that blue was by no means the most luminous part of the spectrum of the light scattered by the sea. He suspected that the eye was endowed with the strange property of enhancing certain regions of the spectrum and suppressing some others in the presence of a slight excess of blue light.

Again, his involvement with gems brought out that the beauty of a gem is assessed by the precise shade and depth of the hue that it displays, i.e. by what one *perceives* of it. And so the characteristics of human vision which plays such a vital role in this perception would therefore be as important in deciding the quality of a gem or mineral as its optical properties.

In 1959 he delivered the first Gandhi Memorial Lecture on October 2nd, the birthday of the Mahatma, and he chose as his subject "Light, colour and vision." As with most of his popular lectures, it was delivered extempore and it was also rather different from the later, written version. The lecture was a masterly survey of how the eye functions as an optical instrument but he also became aware that there were many important questions still to be answered in regard to the perception of colour by the human eye.

The retina and vision

Raman realised that if one were to understand human vision one must explore the retina. He could not put a probe into the eye so he devised a simple method by which one could actually view one's own retina. The observer views a brilliantly illuminated screen, holding before his eye a colour filter (which absorbs completely a limited region of the spectrum while transmitting the rest of it). When the filter is suddenly removed, he sees a highly enlarged view of his own retina (that too in colour) projected on the screen, displaying the response of different areas of it to the incident light. By using a series of filters transmitting different wavelengths, Raman could explore the behaviour of *his* retina under various spectral excitations.

Raman also studied in detail a remarkable but not widely known faculty — namely that the unaided eye is not only able to recognise polarised light but can also locate its plane of polarisation. Sky-light exhibits a high degree of polarisation when observed in a direction transverse to the rays of the Sun. When one views this region of the sky one sees the image of a cross, a dumb-bell shaped bluish brush along the direction of maximum polarisation, and a bright yellow brush of light perpendicular to it. Raman investigated this phenomenon by looking at the spectrum from a diffraction grating with

a polaroid in front of it. From the direction of the brush and its response to colour, the orientation and the optical characteristics of the dichroic molecules in the visual pigments were deduced.

Raman did a series of experiments (some of them a repetition of earlier ones) and found that the eye could discriminate colours corresponding to wavelengths differing by as little as 10 Å. Younger eyes could perceive the difference in colour between the D1 and D2 lines of sodium which are separated by just 6 Å. This established that the transference of radiational energy to the sensing mechanism is a very rapid process not greatly influenced by the thermal agitation of the medium. (If it were, he reasoned that the discrimination could not be finer than 20–25 Å in the yellow.)

Raman was interested in the relationship of brightness and colour. He was familiar with the appearance of nebulae as viewed by a seven-inch telescope which was available to him in Calcutta—faint indistinct patches of light with no colour. During a visit to California, he viewed the same object through the 60-inch and 100-inch telescopes of Mt Wilson Observatory near Pasadena. He recounted vividly that the Ring nebula in Lyra exhibited flaming colours changing progressively from the external edge of its ring to its inner margin while the great nebula in Orion was a blazing area of variegated colour determined by the line emission of the gases of which it is composed. Obviously, the total energy of the light beam which is perceived not only increases the brightness but also considerably affects the sensation of colour. He did set up some simple experiments to demonstrate and measure the intensity at which the colour perception is lost for different colours.

Scintillation of stars

Perhaps the most intriguing observation he made during this period concerned a new type of "twinkling" of stars due to the statistics of photons striking the retina. It would not be possible to perceive a star steadily as a point source of light unless the stream of light corpuscles reaching the particular spot on the retina is continuous and of sufficient strength. Failing this one can expect to perceive the star only in fits and starts depending on the statistics of the arrival of the photons. This picture of fluctuating luminosity would be exhibited most clearly by the fainter stars which are just on the borderline of visibility and would be less evident as the star goes up in the scale of luminosity. This quantum scintillation is altogether different from the well-known phenomenon of the scintillation of stars which has its origin in the local variations of refractive index in the atmosphere. This classical effect is exactly the same for bright and faint stars though naturally more easily observed in the former case. Further the elevation of the star from the horizon has a noteworthy influence. Raman made observations on stars high up in the sky on clear calm nights when the brighter stars in that vicinity did not exhibit variations in intensity. The fluctuating intensity was most obvious when two or more very faint stars fairly close together were viewed and their relative luminosities were constantly compared. He found that these were continually changing and attributed this to photon statistics.

In this connection, it may be mentioned that Raman clearly set out in qualitative terms the presently accepted ideas on the conventional scintillation or twinkling of stars. He was convinced that only by invoking wave-optical principles could this phenomenon be explained. The plane wave-front of light coming from a distant star gets randomly corrugated by the changes of refractivity accompanying density variations in the atmosphere. According to Raman one has to consider the diffraction effects of this ever-changing randomly corrugated wave-front to understand the scintillation and other associated phenomena completely.

While considering the deceptively simple question as to why one was able to see the Milky Way in the sky with the naked eye, Raman set up many experiments to illustrate some strange characteristics of human vision. For example, when a wire mesh was held at the limit of distinct vision and viewed against a bright background, the apertures in the mesh through which the light passes can be perceived—well-defined and clearly separated. As the illumination is progressively decreased a stage is reached when the independent aperture areas cease to be visible and the entire mesh appears as a uniform field—but exhibiting a noticeable enhancement of fluctuations in brightness over its area. These fluctuations increase conspicuously as the illumination is further reduced.

Raman had devised many such beautiful experiments and evolved many empirical theories to explain the perception of light and colour. He personally felt that his contributions to this field were important—as important as those he had made to light scattering. But other workers in this very complicated field held a different view. Experimenters had introduced sophisticated microprobes into the eyes of living animals and combined this with very clever electronics to investigate the visual process. They felt, quite justifiably, that Raman's elementary

experiments, however basic they appeared, were too simplistic for this complex field. Thus, his work remained largely unnoticed. Nevertheless many of Raman's simple observations may not yet have found a satisfactory explanation.

The years of depression

The remarks made so far describe Raman's scientific preoccupations in the last decade of his life. But they do not give a full picture of either his internal or external circumstances, to which we now turn.

Many things happened at this time in his Institute and in the country which affected Raman greatly. The half a dozen graduate students whom he had handpicked to work at his Institute began to leave. By 1960 all of them had gone and he chose not to take any more and (except for two assistants) he was almost all alone. It was then that Raman became a recluse, literally isolating himself by building high walls round his Institute discouraging visitors. He passed through a period of deep depression. He appeared to be in agony, to say the least.

Much of his torment must have sprung from his view of things happening in the country. It seemed to him that scientific administrators, not believing that there was sufficient strength in the country for science to grow, looked outside more and more for inspiration. The policy seemed to be that expenditure (however indiscriminate), would automatically further the progress of science and technology. He felt that the universities, which till then identified and generated talent, were denuded and desertified by the exodus of scientists and teachers to better-paid positions in large, impersonal Government laboratories. Quantity appeared to be mistaken for quality. His attitude towards everyone—especially the Government—became one of suspicion and cynicism. But there were undoubtedly other causes for his depression at a much more personal level. Was it that once his students had left, he lacked the stimulation of discussing science with the young? Or was it because he finally sensed the decline of his creative powers? Or was it just the physiological process of ageing? One does not know.

Flowers and children

It was at this juncture that Raman rediscovered as it were the marvels of flowers and children. It was his interest in colour that made him look at flowers again—for what better material was there which displayed such incredible variations of colour and hue to delight the human eye? Raman was always ardently interested in gardens and gardening. He personally planned, supervised and planted hundreds of flowering and avenue trees at the Indian Institute of Science for which it is now justly famous. When he set up an Institute of his own, the land had not a blade of grass on it and no water was available. He contoured the land so that not a drop of rain drained out and made it a veritable garden by planting many beautiful trees and flowering bushes. He had 168 rose plants in his Institute which he tended with personal care. He studied the spectra of the petals and extracts of hundreds of species of flowers. His Institute became a riot of colour and his laboratory exuded the aroma of a perfumery. When any lady visited him, he presented her with a magnificent bunch of flowers (on which he had experimented) and she thought that the Grand Old Man of Indian Science has chosen her specially for this honour! Twice every year—on January 26th and August 15th— he was at the historic Lal Bagh at the flower show examining the exhibits with his famed pocket direct vision spectroscope — himself attracting a greater crowd than the flowers!

And then he invited children to come. First there was a trickle, then almost everyday he was seen taking school children and college students round his Institute—regaling them with stories, teaching them science, making them observe things in nature, chiding them for not recognising the familiar objects that surround them—be they trees, plants, minerals or rocks—pointing out to them the exquisite beauty of each, showing them his precious gem and mineral collections, demonstrating many acoustical and optical phenomena so familiar to him, testing them for colour blindness, using their young eyes for spectral discrimination experiments. He asked smaller groups to visit the Institute in the evening and after nightfall he showed them the haloes of the moon, and through his 5-inch telescope the mountains of the moon, the rings of Saturn, the moons of Jupiter and of course the great Orion nebula. The Institute was filled with the laughter of children, following old Raman from place to place. His spirits revived, his joy in doing science was restored and the verve he always felt as a teacher came back to him.

The End

On October 2nd 1970 he gave his last Gandhi Memorial Lecture, "On the cochlea and the perception of sound". (Was he thinking of changing his field again?) For the first and only time in his life he asked of his large audience permission to answer their questions sitting down. At the end of October he collapsed in his

laboratory, the valves of his heart having given way. He was moved to hospital and the doctors gave him four hours to live. He survived and after a few days refused to stay in hospital as he preferred to die in the gardens of his Institute surrounded by his flowers. When he was told that there was little chance that he could lead a normal life and that he might have to spend it in bed, he refused medication since he would not care to live in the horizontal position.

On the 19th of November, two days before he died, he told a former student who was present, “Do not allow the journals of the Academy to die, for they are the sensitive indicators of the quality of science being done in the country and whether science is taking root in it or not.” He then gave his vision of the future of his Institute:

> This Institute was created by me in 1948 to provide a place in which I could continue my studies in an atmosphere more conducive to pure research than that found in most scientific institutions.
>
> To me the pursuit of science has been an aesthetic and joyous experience. The Institute has been the haven where I could carry on my highly personal research.
>
> This personal character of the Institute should obviously change after me. It must blossom into a great centre of learning embracing many branches of science. Scientists from different parts of India and all over the world must be attracted to it.
>
> With its beautiful gardens, large libraries, extensive museums, I feel that the Institute offers a perfect nucleus for the growth of a centre of higher learning.
>
> Science can only flower out when there is an internal urge. It cannot thrive under external pressures. Fundamental science cannot be driven by instructional, industrial, governmental or military pressure. This is the reason why I decided as far as possible not to accept money from Government.
>
> I have bequeathed all my property to the Institute. Unfortunately this may not be sufficient for the growth of this centre of learning. I shall therefore not put it as a condition that no governmental funds should be accepted by the Institute. I would however strongly urge taking only funds that have no strings attached.

The same evening he held a meeting of the Board of Management of the Institute, conducted the proceedings from his bed, and when it concluded he dictated the minutes. He died peacefully early in the morning of the 21st of November, 1970.